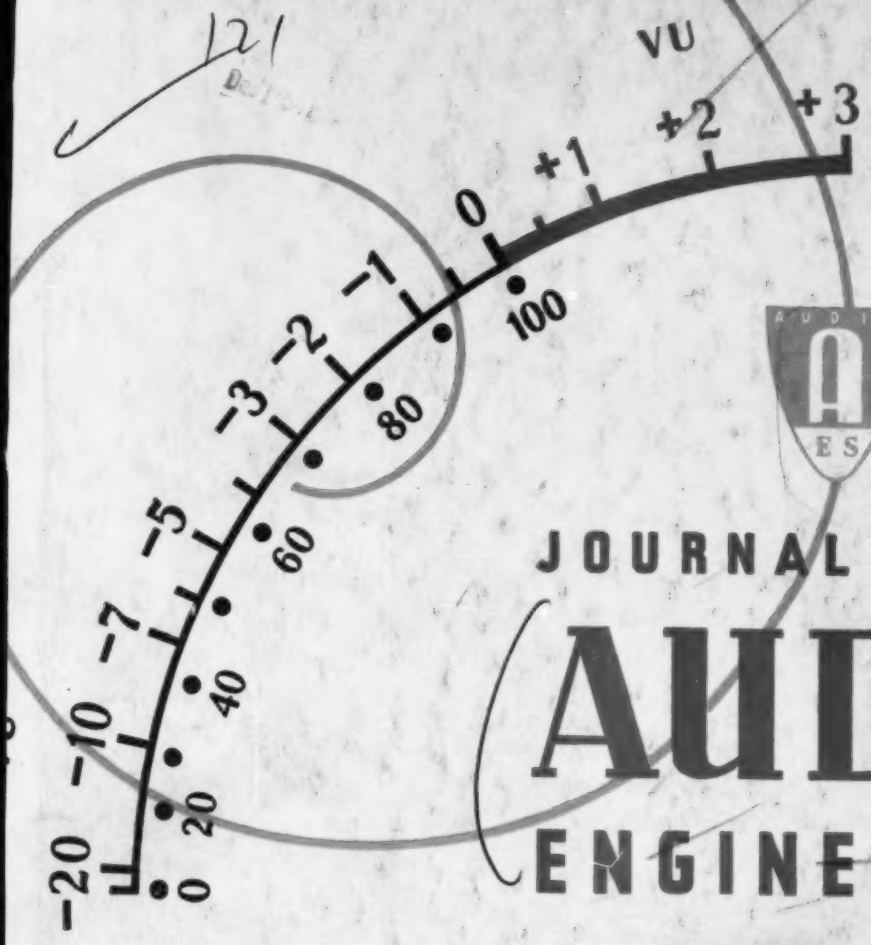

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Survey of Flux-Responsive Magnetic Reproducing Heads*

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A magnetic reproducing head which generates a signal voltage substantially proportional to the magnitude of the intercepted magnetic flux is commonly referred to as a flux-responsive or magnetostatic head.

The fundamental mode of operation, the different approaches to practical solutions, and the characteristic features of this type of head are described. The explanations are illustrated by a number of cases which have been either proposed or practically executed by various organizations and investigators. A bibliography is given, including brief abstracts of pertinent patents and other publications.

EVER SINCE the inception of magnetic recording there has been essentially only one method of signal reproduction in practical use. This method consists in moving the magnetic record relative to the reproducing head, thus causing the magnetic flux which leaves the record to induce corresponding signal voltages in the head windings.

Using the same type of magnetic head and the same type of electronic gear—sometimes even physically the same units—the reproducing process is, magnetically, the exact reversal of the recording process. This approach is, indeed, the simplest and most economical one and has, therefore, been almost universally adopted.

This paper will present a review of the exceptions to this rule and of their modes of operation.

A brief look at some fundamental aspects of the conventional playback process will be helpful. A part of the magnetic flux which leaves the surface of the recording medium enters the core structure of the reproducing head and interlinks with the winding on this structure. When there is relative and uniform motion between the head and the recording medium, the interlinking flux will change in accordance with the recorded signal and an electromotive force proportional to the rate of this change will be induced in the head winding. This electromotive force is the conventional playback voltage.

Whenever the recorded signal shows only very little

* Presented before the Audio Engineering Society, Los Angeles, on February 4, 1954.

variation with time, or none at all, the corresponding rate of flux change in the head will result in an either unusably low or altogether vanishing playback voltage. It is under such conditions that a reproducing head which responds to the magnitude of the signal flux, instead of its rate of change, becomes desirable if not imperative. The need for such flux-responsive, or magnetostatic, heads has been on a steady increase, especially in the fields of low-frequency measurements, industrial control, computers, and other magnetic memory devices.

In this connection it may be of interest to point to somewhat analogous conditions which exist with transducers in fields other than magnetic recording. The best example is probably that of phonograph pickups. There, the so-called velocity type, as represented by the electromagnetic or the electrodynamic systems, corresponds to the conventional magnetic reproducing head; the amplitude, or displacement pickup, represented by piezoelectric or capacitive systems, is the counterpart of the flux-responsive head. Very similar conditions can be found with velocity and displacement types of microphones and many other transducers. The case of optical sound reproduction, on the other hand, represents an amplitude-responsive system which has no velocity-type counterpart.

There is another characteristic feature of flux-responsive heads which must not be overlooked. It is the self-evident fact that the signal reproduced by a flux-responsive head is an accurate facsimile of the recorded flux pattern and, therefore, of the original information. This is in contrast to the performance of conventional heads which, by the very principle of their operation, produce a signal proportional to the time derivative of the recorded flux pattern. This behavior is of no further significance in most audio applications and many others where phase shift has been found to be unimportant. However, when an exact replica of the originally recorded wave form is required, additional measures become necessary with conventional reproducing heads. Such measures may consist in the use of some form of carrier frequency-recording system, or of an integrating circuit to revert the reproducing signal to its original shape and phase. Both methods accomplish their purpose but also have their shortcomings. The former requires an unduly high record medium speed, and the latter presents substantial difficulties for wide-frequency bands. Furthermore, neither one is operative at complete standstill of the recording medium relative to the reproducing head.

Figure 1 illustrates the effect of phase shift more clearly. The upper row of curves shows arbitrarily chosen examples of three different signal wave forms: a sine wave; a sine wave with a 50% second harmonic content; and a square wave. Assuming that these signals were properly recorded, that is, without distortion, the curves also represent the shape of the flux distribution in the recording medium.

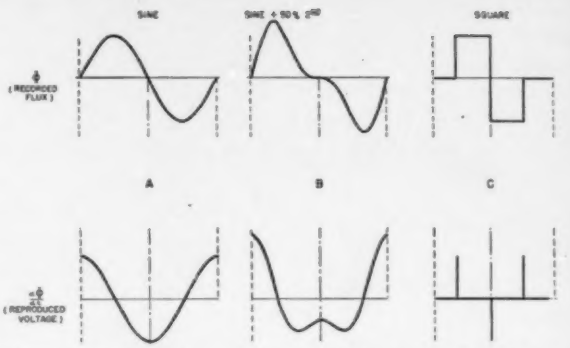

FIG. 1. The wave form differentiation in a conventional reproducing head.

The corresponding signal voltages reproduced by a conventional head, obtained by differentiation of the flux curves, are illustrated in the bottom row of the figure. It can be seen that the sine wave has remained unchanged in shape but was retarded in phase by 90 electrical degrees. In examples B and C the differentiation has caused basically similar but visually much more pronounced effects. The deviation of the differentiated wave shape from the original one is, of course, the greater, the more the shape deviates from a sine wave; an extreme example of this type is shown by the square wave which transforms, after differentiation, into nothing more than individual spikes.

For a more detailed description of the specific features of flux-responsive heads, it may first be of interest to see just what fundamental possibilities exist at all of obtaining a playback signal from a magnetic record. The schematic of Fig. 2 gives a survey of such possibilities. Not only the approaches which have resulted in operative and practical structures have been included but also the ones which have been merely suggested in the literature or in patents. To

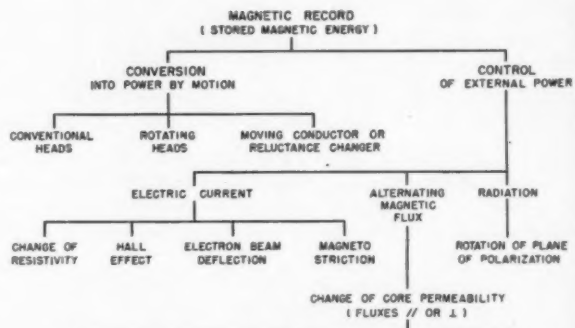

FIG. 2. The fundamental possibilities of producing a signal from a magnetic record.

complete the picture, a few more effects have also been noted which offer, at least theoretically, additional possibilities of signal reproduction. The following comments on the different approaches indicated in Fig. 2 are presented in the order of the arrangement shown in the schematic. A brief description of specific solutions will be found in connection with some of the respective literature references.

The "raw material" available for the production of a playback signal is the potential energy stored in the magnetic recording medium in the form of remanent magnetization, varying in accordance with the original signal. In order to translate this into a usable effect, that is, into a flow of power, there are two fundamental approaches. One can either utilize the principle of relative motion between the available magnetic field and a conductor and thus generate electric power, or one can use the field to control some external flow of power. These two possibilities are represented by the two main subdivisions of the schematic in Fig. 2.

The first group, "Conversion into Power by Motion," includes, as the most important representative, the conventional magnetic reproducing head. Its description does not belong here; of the very numerous publications dealing with it, some of the more recent ones might be mentioned, however.[1-3] A comprehensive bibliography up to 1948 can be found elsewhere.[4]

The rotating head also belongs to the class of "Conversion by Motion," since it generates the signal voltage by means of its own motion relative to the recording medium; it can, therefore, produce a signal even from a recording medium at standstill. The distinction from a flux-responsive head in the strict sense of the word can be based on the very large increment of information (large in comparison with its resolving power) which the head explores during each scanning period. The device can, therefore, be looked upon as a transition between conventional and flux-responsive heads. The fundamental idea of a rotating head appears to have originated, independently, in France[5] and in Germany;[6] modifications were later suggested in this country.[7]

The next member of the group under discussion is a structure which supplies the necessary motion by vibrating a single conductor in the signal field of the recording medium. A device of this type described in the literature[8] was not primarily intended to serve as a magnetic reproducing head but could meet all the necessary requirements. Because of its extremely small exploring area—in contrast to the rotating head—it can be classified as a flux-responsive head.

A different way of using motion for the generation of signal power is the periodic variation of the reproducing-head reluctance by mechanical means. This can be done, for instance, by inserting a small rotating or vibrating soft iron armature into the magnetic structure of the head. The resulting signal then consists of a carrier frequency which is amplitude modulated by the field of the recorded signal. This operation clearly classifies the head as a flux-responsive one.

Turning to the second main group of Fig. 2, "Control of External Power," it becomes apparent that the available possibilities are much more numerous than in the first group. Very few of them, however, are applicable to practical solutions, and a good many have no more than curiosity value. All possibilities of the whole group lead to flux-responsive heads only, since they all have the common feature of utilizing the signal flux for controlling some external flow of power. This power may be supplied by electric current, by an alternating magnetic field, or by radiation of some kind.

The control of electric current could conceivably be accomplished by the change of resistivity of certain materials in a magnetic field, or by the Hall effect; it seems, however, that neither approach has ever been attempted. The effect of magnetostriction could be utilized to constrain a vibrating body which controls an electric oscillator. Patents based on this principle exist[9] but do not refer, except for one,[10] to the specific application in magnetic recording. The one exception is, actually, an energy "converter," not a "controller," but may be mentioned in this connection because of its relationship to the preceding reference.

---

[1] E. D. Daniel, "The Influence of Some Head and Tape Constants on the Signal Recorded on Magnetic Tape," *Proc. I.E.E.*, pp. 168-175 (1953).

[2] O. Kornei, "Structure and Performance of Magnetic Transducer Heads," *J. Audio Eng. Soc.*, **1**, 225-231 (1953).

[3] W. K. Westmijze, "The Principle of Magnetic Recording and Reproduction of Sound," *Philips Tech. Rev.*, **15**, No. 3, 84-96 (September, 1953).

[4] S. J. Begun, *Magnetic Recording*, pp. 133-134, Murray Hill Books, New York, 1949.

[5] Gabrilovitch, U. S. Pat. 2,170,751 (March, 1937-August, 1939; in France, March, 1936). Basic thought of rotating magnetic head and its use in the transmission of intelligence.

[6] E. Schueller (A.E.G.), German Pat. 721,198 (August, 1938-April, 1942); equivalent U. S. Pat.: Alien Property Custodian 291,620. Special structure of rotating head, the core of which consists of integral stack of laminations common to all individual heads.

[7] A. L. Williams (The Brush Development Co.), U. S. Pat. 2,424,295 (July, 1943-July, 1947). Two-pole head rotating at high speed in contact with record medium, generating amplitude-modulated carrier.

[8] D. M. Chapin, "A Sensitive Magnetometer for Very Small Areas," *Rev. Sci. Instr.*, **20**, 945-946 (1949). 60-micron thick wire, attached to and driven by a 49-kc quartz crystal with an amplitude of ½ micron, generates a voltage of driving frequency and proportional to explored field strength.

[9] B. E. Parker, U. S. Pat. 2,551,848 (April, 1948-May, 1951). Frequency modulation of oscillating piezoelectric crystal effected through bonded layer of magnetostrictive material. Other U. S. patents dealing with related subjects: 2,101,272; 2,571,019; 2,636,135.

[10] O. Kornei (Clevite Corporation), U. S. Pat. 2,683,856 (January, 1951-July, 1954). Flux picked up from the magnetic record causes a magnetostrictive structure to constrain a piezoelectric member, thus generating a signal voltage. Other forms of magnetostrictive-piezoelectric transducers are also described.

The idea of using the record magnetization to control electric current in the form of an electron beam first appeared in a German patent,[11] but not much significance was attached to it. A much more specific patent[12] issued in the United States has formed the basis for more recent and extensive work.[13] As appealing as the magnetic control of an electron beam appears, it has two inherent shortcomings. One is the comparatively great bulk required for each head; the other is the very low field strength (of the order of, and below, that of the earth field) available for the control. This, in turn, necessitates extensive shielding and limits the signal-to-noise ratio.

A different though closely related approach[14] to the same problem is based on the emission of secondary electrons and probably permits a somewhat more efficient utilization of the signal field strength than in the former case.

Another possible method involves use of electron beam deflection for the purpose of making a relatively extended magnetic record pattern visible on a tube screen.[15]

The group headed "Radiation" has apparently produced only one single suggestion in the patent literature.[16] Unusual as this approach is, it seems to have remained of purely academic interest.

The remaining group of Fig. 2, the one which utilizes the control of an alternating magnetic flux by means of the signal field, is, by far, the most important one. In fact, all flux-responsive heads of practical significance at the present time belong to this group. The fundamental principle common to all these devices is the dependence of the permeability of a magnetic core on its magnetization. Depending on the way in which the change of permeability is obtained and the different effects which can be accomplished, a number of specific solutions are again possible.

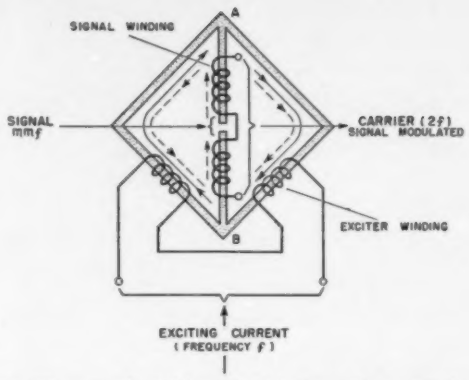

FIG. 3. The magnetic bridge principle for a flux-responsive head.

In most cases the controlling signal flux and the controlled alternating flux pass through the head core in the same direction. Whenever this approach is chosen, special measures have to be taken which permit the mutual interaction between the two fluxes in the head core but prevent, at the same time, any of the alternating exciter flux to pass across the transducer gap. If this precaution were not taken at least a partial erasure of the signal under reproduction would occur. In order to accomplish the desired effect a balanced magnetic bridge structure is used, the fundamental principle of which is schematically shown in Fig. 3.

The familiar arrangement of a Wheatstone bridge, transposed into magnetic terms, can be readily recognized. All members of the bridge are composed of sections of magnetic material instead of electric impedances, and the usually applied source of electromotive force has been replaced by windings around two arms, i.e., by a source of magnetomotive force. Assuming that the structure and the windings are symmetrical, the bridge will be balanced and no magnetomotive force will exist between the points A and B when a current is fed into the exciter windings. In further consequence there will be no voltage generated in the signal winding applied to the bridge member. When an external magnetomotive force is injected into the gap of the bridge member (corresponding to the gap of a reproducing head), a corresponding flux will flow and close through the arms of the bridge, as indicated by the dashed-line arrows in Fig. 3. These arms, however, also carry the alternating exciting flux, as indicated by the solid-line arrows; their magnetic reluctance will, therefore, vary twice during each cycle in accordance with their instantaneous magnetization. Accordingly, a strong second harmonic of the exciter frequency (besides the fundamental and higher harmonics) will appear across the signal winding and can be used as a measure of the intensity of the injected field strength. In

[11] U. Fusban-Lorenz, German Pat. 680,680 (October, 1936-August, 1939). A square frame structure, without air gap, picks up tape flux through one corner of square. Two biased windings, on two different sides of square, are used to unbalance a bridge circuit. Patent also suggests control of electron beam by flux from recording medium.

[12] A. M. Skellett (B.T.L.), U. S. Pat. 2,165,307 (March, 1937-July, 1939). Combination of special cathode-ray tube with external armature acting as magnetic reading head. Flux closes through internal armature which deflects beam, thus generating corresponding plate current variations.

[13] A. M. Skellett, L. E. Leveredge, and J. W. Gratian, "Electron-beam Head for Magnetic Tape Playback," *Electronics*, **26**, 168-171 (October, 1953).

[14] F. Gray (B.T.L.), U. S. Pat. 2,657,377 (May, 1951-October, 1953). A cathode-ray tube with thin window, permeable to magnetic flux from the recording medium which contacts the window externally. Cathode beam striking window releases secondary electrons whose emission is modified by magnetic record pattern, thus generating playback signal. U. S. Pat. 2,657,378 (same data as above) is closely related.

[15] R. L. Miller, "Visual Monitor for Magnetic Tape," *J. Soc. Motion Picture Television Engrs.*, **61**, 309-315 (1953). Ribbon-shaped electron beam scans tape crosswise at grazing incidence, producing a variable area image on screen.

[16] O. L. O'Dea (RCA), U. S. Pat. 2,485,839 (April, 1948-October, 1949). Modulation of a beam of light by the magneto-optic effect. Magnetic field of reproducing head is used to rotate plane of polarization in a sheet of glass inserted in magnetic circuit.

order to obtain an indication proportional to the amplitude of this second harmonic, it is merely necessary to pass the total signal output through an appropriate band-pass filter and demodulate the resulting amplitude-modulated carrier.

The remaining signal still suffers from a serious defect. It will be noted that its magnitude is an indication only of the magnitude of the injected signal magnetomotive force, regardless of its direction. As a consequence, for instance, frequency doubling of any injected alternating signal would occur. The next two figures will aid in giving a more detailed discussion of this situation and how it can be corrected.

Figure 4 is a schematic transfer characteristic showing the amplitude, e, of the second harmonic of the exciter frequency versus the signal field strength, H. It can be shown[17,18] that the interdependence of these two quantities is not strictly linear but sufficiently so for most practical purposes, at least over a limited range. Because of the symmetry of the transfer function about the ordinate, it is clear that any field strength, whether positive or negative, will result in the same magnitude (though opposite phase) of second-harmonic output; this means, essentially, frequency doubling of the signal, as pointed out before.

The obvious way out of this situation is to place the operating point about which the signal field strength varies off the origin O, say at P. This point should be chosen so that it lies centered within the straightest portion of the transfer curve. In order to accomplish this shift a bias field, H_0, may be introduced, for instance, by supplying a constant direct current through the signal winding, thus generating a constant output, e_0. A superimposed signal field, $\pm H_s$, will then cause the total output voltage to vary between e_{max} and e_{min}.

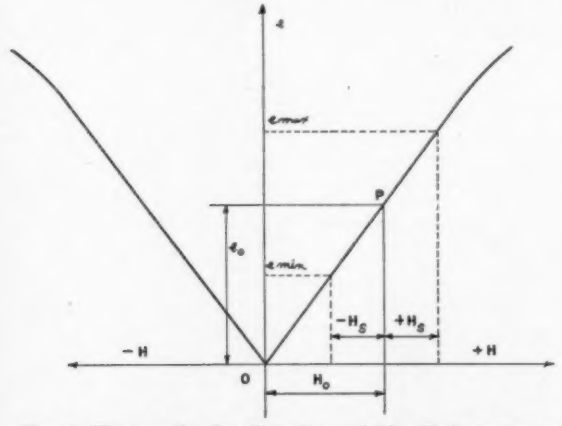

FIG. 4. The transfer function of a variable reluctance type of magnetic transducer (schematic).

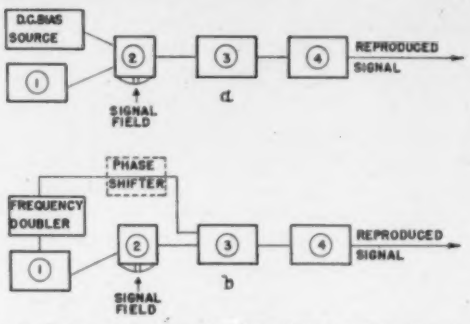

FIG. 5. The use of a constant bias field (a) and of second harmonic injection (b) for linearizing the transfer function. (1) Generator of exciter frequency f. (2) Variable reluctance type of flux-responsive head. (3) Pass band amplifier (center frequency $2f$). (4) Demodulator.

There is still another way of shifting the operating point to P. Instead of introducing the mentioned dc bias field H_0 to cause the mean voltage, e_0, to be generated within the flux-responsive head, one can subsequently inject such voltage into the output of the head, omitting the dc field altogether. It will be clear from Fig. 4 that both approaches lead fundamentally to the same result. The use of second-harmonic injection, instead of dc bias, seems to result in a somewhat lower noise level and in some cases offers certain circuitry advantages. The method appears to have been suggested first in reference 26, quoted later.

These two methods of preventing signal frequency doubling are further illustrated in the self-explanatory block diagrams of Fig. 5. It should be added that the phase shifter indicated in Fig. 5b may not be actually required as long as the signal voltage generated in the head and the subsequently injected double-frequency exciter voltage are in phase, or very closely so. Because of the vector summation of the two, an increasing phase deviation causes increasing distortion of the carrier modulation, i.e., of the final signal.

Another phase-sensitive detection method, somewhat related to the one just described, was published in a different connection.[19]

Various examples of flux-responsive reproducing heads utilizing the core reluctance change in conjunction with the

[17] E. P. Felch *et al.*, "Airborne Magnetometers for Search and Survey," *Trans. AIEE*, **66**, 641-651 (1947). Includes derivation and discussion of magnetometer transfer function.

[18] E. C. Schurch and F. R. Schleif, "A Magnetic Tape Oscillograph for Power System Analysis," *Trans. AIEE*, **70**, 1296-1300 (1951). A system using a flux-responsive head for the reproduction of a transverse magnetic recording. Operation is based on reluctance change in small portion of magnetic circuit of head, using exciter frequency of 20 kc.

[19] William A. Rote, "Magnetic Converter D.C. Amplifier," *Electronics*, pp. 170-173 (December, 1953). Describes a magnetic modulator used as a chopper. The second harmonic of the exciter frequency, derived from the modulator, is added with 90° phase shift to the exciter fundamental. The resulting vector sum is proportional to magnitude and direction of signal.

described magnetic bridge arrangement can be found in the literature.[20-22] An interesting variation is the one in which the bridge circuit occupies only a small portion of the total magnetic core.[18]

The permeability change can also be utilized to control the impedance or inductance of a winding instead of the reluctance of a core. It should be remembered, though, that all these approaches are based on exactly the same phenomenon; it is merely the manner in which they are used which distinguishes one from the other.

The change of impedance of a winding is suggested in what is possibly the earliest reference to any flux-responsive head, the German patent[11] already referred to. Two more examples belonging in this class can be found in the patent literature.[20,23]

In all the devices discussed so far, which operate with a controlled alternating flux, this flux and the signal flux were passing through the head core in the same direction. It is possible, however—as has been indicated in the schematic of Fig. 2—to have the two fluxes perpendicular to one another. The interaction of mutually perpendicular fields in ferromagnetic materials[24] has been much less explored than that of parallel fields but has nevertheless found applications in at least two constructions of flux-responsive heads. The first specific suggestion of this type seems to have been made in a Swiss patent.[25] A fundamentally related but structurally quite different device[26] was reported some time ago in this country. A recently issued British patent also deals with a similar structure.[27] In either case the playback signal is obtained, as with parallel fluxes, in the form of an amplitude-modulated carrier the frequency of which is double the exciter frequency.

By the very principle of mutually perpendicular signal and exciter fluxes there exists no coupling between them. Thus, the exciter flux is excluded from appearing across the transducer gap without any additional measures. This feature can, in some cases, offer structural advantages over the parallel flux method which requires the previously described bridge arrangements.

In conclusion it may be in order to mention briefly the limitations and special features which are, at this time, common to all types of flux-responsive heads. There is, in the first place, a comparatively low signal-to-noise ratio which seldom exceeds, and is usually below, 40 db; there is the fact that the longest wavelength to be handled determines the longitudinal head dimension, which may therefore appear rather bulky in some cases; and there is the always existing possibility of a minor "zero-shift" of the carrier amplitude controlled by the head. It should also be pointed out that even a flux-responsive head does require a flux gradient (i.e., a magnetomotive force) across its gap in order to function—it cannot detect a perfectly uniform magnetization.

Flux-responsive heads are not yet commercially available. Their steadily increasing importance, however, has prompted intensified industrial efforts which are likely to yield results before long.

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[20] E. Peterson (B.T.L.), U. S. Pat. 2,608,621 (October, 1949-August, 1952). Various forms of magnetic bridge structures to serve as flux responsive heads and based on either variation of core reluctance or winding impedance.

[21] D. E. Wiegand, "A Flux-Sensitive Head for Magnetic Recording Playback," *Proc. I. R. E.*, 41, 424 (1953). Abstract only; very similar to approach of reference 20.

[22] D. H. A. Hageman, "A Head for Static Reading of Magnetic Recordings," M. S. Thesis, The Massachusetts Institute of Technology, June, 1951. Theory and construction of magnetometer-type head. Intended for pulse work; obtained about 30 pulses per inch and 10:1 signal-to-noise ratio.

[23] L. L. Burns, Jr. (RCA), U. S. Pat. 2,536,260 (December, 1948-January, 1951). A flux-responsive head with part of its magnetic circuit consisting of a balanced bridge structure. The material of the bridge is ferrite with a strong permeability-*vs*-magnetization dependence, suitably biased by a permanent magnet. A winding on the bridge determines the frequency of an oscillator.

[24] R. M. Bozorth, *Ferromagnetism*, D. Van Nostrand Company, pp. 552-554, New York, 1951.

[25] W. N. Gerber (Silectra), Swiss Pat. 270,675 (1949-December, 1950). A magnetic ring structure which can serve—among other purposes—as a magnetic reproducing head is intersected by a second ring so that the two structures are mutually perpendicular and have one section in common. An ac winding on the second ring varies its reluctance and, by virtue of common section, also that of ring head.

[26] S. M. Rubens and A. B. Bergh, "A Magnetostatic Reading Head," *Proceedings of the Department of Defense Symposium on Magnetic Recording*, Fifth Symposium on Acoustics-in-Air Research and Development (March 1, 1954). Exciter current flows through a lamination which forms part of magnetic structure of head. Circular exciter flux is thus perpendicular to signal flux through lamination. Signal winding is applied over two such laminations, oppositely passed through by exciter current, to cancel fundamental from output.

[27] H. W. Nordyke, Jr. (I.B.M.), British Pat. 709,655 (October, 1951; in U. S., December, 1950–June, 1954). Describes head structures much like those of references 20 and 25.

Resonance, Tracking, and Distortion

An Analysis of Phonograph Pickup Arms

R. E. CARLSON*

INTRODUCTION

THE FUNCTION of the pickup arm is not dissimilar to that of the speaker housing, in terms of the symmetrical location of each to the other in the complete reproducing chain, and in terms of the contribution of each to the over-all performance of any sound reproducing system. Until comparatively recently, but slight attention was given to the design and construction of appropriate speaker housings, although it is now well recognized that this portion of the complete system may not be disregarded where excellent results are desired. The comparable interrelationship between pickup arm characteristics and pickup performance (and hence, of course, over-all performance) seems to have attracted much less attention.

It is the purpose of this survey to bring together the available data with regard to pickup arms in a form which, it is hoped, will be helpful to the user of such equipment rather than to the designer, for whose benefit many of the existing discussions of the subject seem to be directed. The principal topics to be considered are:

1. Arm resonances, lateral and torsional.
2. Effects of large masses on arm performance.
3. Damping and its effects.
4. Effects of using offset arms.
5. Distortion arising from tracking errors.
6. Necessity for careful placement of the arm with respect to the record center.

It is important to remember that the increasing precision of recording techniques and the constant and impressive improvement in amplifiers, transducers, and other components combine to place more and more stringent demands on the performance of the pickup arm. Slight errors or distortions become more important as perfection is more closely approached. Furthermore, effects which may be subtle, or which may occur only under certain circumstances, take on increased significance. Indeed, the art of sound recording and reproduction has advanced to the point where it is almost safe to say that obvious defects are nonexistent. But effects —or defects—which contribute to listening fatigue, to distortion at points of high modulation, to a general lack of clarity, or to anything which, with time, will render unsatisfactory the performance of the system cannot be overlooked. Such "second-order" effects lie in the field where the greatest advances are yet to be made, and hence the field to which it is altogther proper to turn our attention.

I. PROBLEMS ASSOCIATED WITH ARM RESONANCES AND PROPER TRACKING

Arm resonances can, and do, play an important part in the performance of a system. Figure 1 gives a graphic picture of the results to be expected from the use of either of two lightweight, plastic arms with an otherwise good system. The second curve in Fig. 1 represents the performance of an arm of more rigid construction than that represented in the

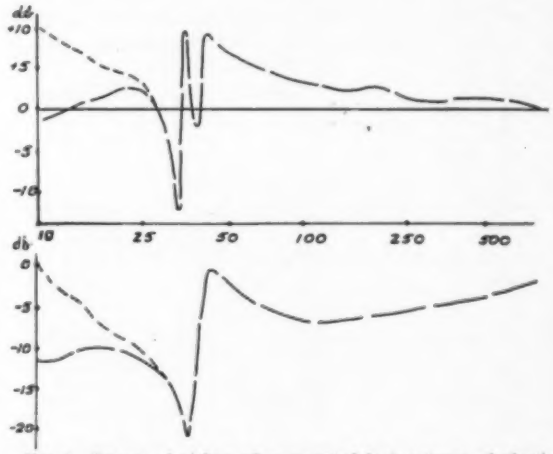

FIG. 1. Output of pickup when mounted in two types of plastic arm. (Dotted curve below 25 cps calculated for equalization continued to 10 cps.) (Fairchild Recording Equipment Co.)

* Consultant to Fairchild Recording Equipment Co.

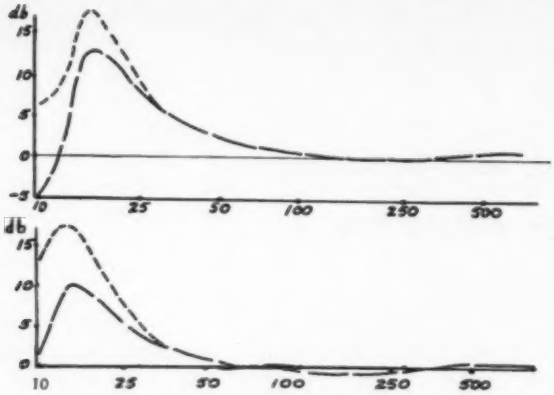

FIG. 2. Output of pickup when mounted in two "transcription" arms. (Fairchild Recording Equipment Co.)

first curve, but neither could be considered as remotely approaching the performance of other good components. It is a fact, nevertheless, that many installations are made using such arms in conjunction with an otherwise first-class system. Some "transcription" arms leave much to be desired also, as may be seen from the curves of Fig. 2, the first curve being that of a medium-priced arm and the second that of a rather expensive arm. (Figures 1 and 2 were made with a variable reluctance type of cartridge of good quality. All the curves[1] were made with a preamplifier whose response is shown in Fig. 3, which is considered typical of a good preamplifier response.)

Resonance, Dynamic Mass, and Compliance

The variations from ideal performance seen in Figs. 1 and 2 are caused by resonances between the arm and the cartridge. Although many modes of vibration are possible, the ones in which we are chiefly interested are the fundamental resonant frequency (determined by the compliance of the stylus assembly and the moment of inertia of the arm assembly about its vertical pivot) and torsional resonances (i.e., a rotational vibration of the arm about a longitudinal axis due to insufficient rigidity of the arm itself). The high-frequency resonance determined by the dynamic mass of the stylus assembly itself and the compliance of the record material are not considered here.

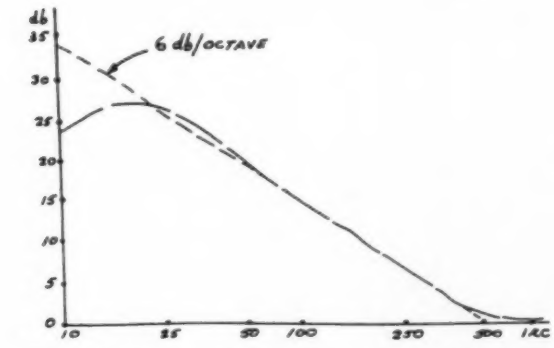

FIG. 3. Low-frequency equalization of preamplifier used in tests. (Fairchild Recording Equipment Co.)

[1] The higher bass response indicated below 30 cps would be obtained if equalization continued at 6 db/octave to 10 cps.

For many reasons it is often more convenient to employ the concept of equivalent mass as referred to the stylus tip rather than moment of inertia. The relationship derives from fundamental definitions and is given in Fig. 4, where I_p is the moment of inertia of the arm about the vertical pivot, P, and L is the distance from vertical pivot to stylus. When this concept is employed, the rotating system (shown in plan view at the right of Fig. 4) reduces to the usual case of simple harmonic motion shown at the left. (The more

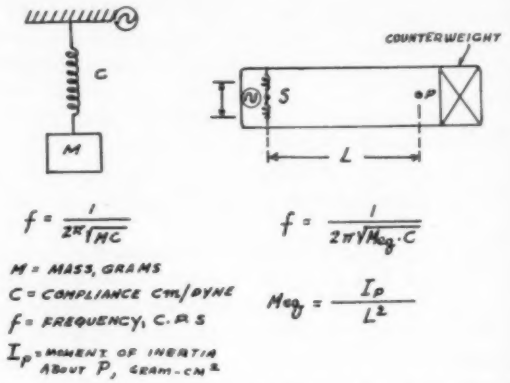

FIG. 4. Simple harmonic motion in translation (left) and rotation (right). (Fairchild Recording Equipment Co.)

familiar situation in simple harmonic motion is perhaps that in which the driving force is applied to the mass, rather than to the support as it is here, but for practical purposes the performance may be considered identical. The precise difference between the two cases may be reviewed by reference to any standard textbook on vibratory motion.)

It is all too easy, since it is so convenient, to assume tacitly that the body of the pickup stands still while the stylus and the associated "moving" elements follow the modulation of the groove. That this is not actually true may be more clearly brought to mind by considering an extreme case in which the "moving" mass of the pickup was made approximately equal to the "fixed" mass. Clearly, in such a structure a large part of the energy transmitted by the groove modulation would be transferred to kinetic energy of the "fixed" mass, the exact amount depending on the nature

of the coupling between the two parts. Since the electrical output of a magnetic cartridge is proportional to the *difference* in the velocities of the two parts, we should be far from the ideal response in such a case, and the response of a displacement-sensitive transducer would also be adversely affected.

One function of the arm is to maintain this relative immobility of the pickup as a whole. At the same time it must allow the slow motion of the groove spiral to be followed by the pickup, and the arm thus resembles a mechanical low-pass filter. This filter cannot have an infinite slope, and hence there may be some interaction of functions. It may also introduce undesirable resonances at the transition point.

The fundamental resonance can best be handled by moving it to a frequency which is low enough to be out of the useful audio range, as well as out of the range of the principal rumble and motor vibration frequencies. In practice this means that the resonance should occur at or below about 20 cps (motor vibration frequencies are chiefly 30 and 60 cps). It is furthermore desirable to limit the amplitude of arm motion at resonance, which may be achieved by damping.

Torsional resonances usually occur at rather higher frequencies than the lateral resonance just described, since the moment of inertia of the arm is so small about a longitudinal axis. The best approach to this problem seems to be to increase the torsional rigidity of the arm so that for all practical purposes no torsional vibration can exist. Such consideration leads to a search for the structure inherently most rigid for a given mass (for, as we shall see, it is desirable to keep arm mass low). A tube of circular cross section is admirable in this respect, but one of square cross section is practically as good for a given mass and offers, in addition, certain practical advantages in this application.

One obvious approach to the problem of lowering the fundamental resonant frequency is to increase the equivalent mass of the arm. The extent to which this solution may be applied is limited by other considerations. Chief of these is the fact that, as the equivalent mass at the stylus position is increased, the forces required for lateral or vertical accelerations of the whole arm are increased in direct ratio, since

$$F = Ma$$

Unfortunately, records are eccentric and often warped. Eccentric records require less acceleration of the mass than do warped ones, principally because of the fact that even small eccentricity introduces intolerable wow. In addition, eccentricity is a "once-around" phenomenon, whereas a warp is quite apt to occur more than once per revolution with correspondingly larger accelerations. Hence it is desirable to keep the equivalent mass low, especially from the point of view of tracking warped records.

The alternative approach is to increase the compliance of the stylus suspension. Reference to the fundamental relationship (given in Fig. 4)

$$F = \frac{1}{2\pi\sqrt{M_{eq}\,C}}$$

shows that this is equally effective. For example, to achieve a resonant frequency of 20 cps with a pickup of comparatively low compliance, say 0.5×10^{-6} cm/dyne, an equivalent mass of 127 grams would be needed. Increasing the compliance to 2.0×10^{-6} cm/dyne would decrease the necessary mass by the same factor, or to about 32 grams. In addition to illustrating the obvious advantage of higher compliance, these figures also serve to point up the necessity of considering the arm and cartridge as a unit.

Vertical Stylus Forces

The relationship between equivalent mass and undesired forces due to either vertical or horizontal accelerations may conveniently be illustrated by a numerical example. Referring to Fig. 5 we see represented an arm with horizontal pivot at P and mass counterbalanced. The net unbalanced force will be seen to be 7 grams (the nominal stylus force), and from the disposition of the assumed 57- and 250-gram masses the equivalent mass may be found to be 67 grams. This is a reasonable figure if we adopt an average value for C of 1.0×10^{-6} cm/dyne (for common magnetic pickups), since the fundamental resonance will be about 19.5 cps.

It should perhaps be stated parenthetically at this point that a popular conception, or misconception, of such a system is that it matters little, if at all, how the "nominal stylus force" is obtained. If we were concerned solely with playing perfectly flat and perfectly concentric records, this would be nearer the truth. But when playing any but perfect records we must consider the dynamic characteristics of the arm, which are determined by the moment of inertia of the entire moving system. The situation is very similar to that presented in Atwood's machine, shown at the left of Fig. 5.

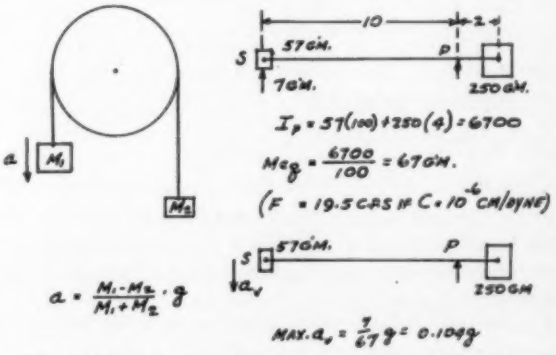

FIG. 5. Dynamic characteristics of mass-counterbalanced arm for vertical accelerations. (Fairchild Recording Equipment Co.)

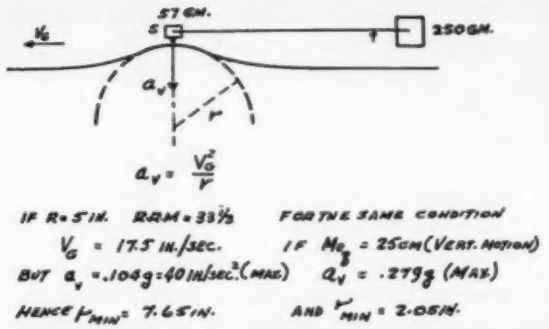
57 GM.
250GM.
a_v
r
$a_v = \frac{V_G^2}{r}$
IF R=5IN. RPM=33⅓ FOR THE SAME CONDITION
V_G = 17.5 IN./SEC. IF M_{eq} = 25GM (VERT. MOTION)
BUT a_v = .104g = 40 IN/SEC² (MAX.) a_v = .279g (MAX)
HENCE r_{MIN} = 7.65 IN. AND r_{MIN} = 2.05 IN.

FIG. 6. Side view of record warp (r = radius of curvature of warp at point under consideration). (Fairchild Recording Equipment Co.)

There is, of course, a difference in the two cases, since in the motion of the arm the two masses do not have the same linear acceleration, but an exactly similar computation may be applied in the case of the arm if the dynamic mass is used in place of $M_1 + M_2$ and the unbalanced force (in gravitational units) is used in place of $M_1 - M_2$. Hence, for the arm pictured the greatest possible vertical acceleration (downward) is $7/67g$, or $0.104g$ (where g is the acceleration due to gravity). If the vertical acceleration required by a given warp were greater than this, the stylus would leave the groove.

The same idea may be expressed in terms of the minimum radius of curvature of a warp which could be followed by the stylus. In Fig. 6 we assume the stylus to be at a 5-in. radial distance from the center of a 33⅓-rpm record. As indicated in Fig. 6, the minimum radius of curvature under such conditions is 7.65 in. Of course, records do not tend to warp in the form of a sine wave or of a circular arc. The more normal cross section of a warped record would show two essentially straight lines connected by a short curve due to the plasticity of the material. Hence such curvature may easily be equaled or exceeded in practical cases.

Under the conditions assumed in Figs. 5 and 6, the stylus would be "about to leave" the groove—i.e., the stylus force would be zero. But performance deteriorates long before stylus force is reduced to zero. If we assumed a warp radius of curvature of $3 \times r_{min}$ or about 23 in., the vertical acceleration, with other conditions the same, would be about $0.035g$. Hence the stylus force would be

$$F_s = 7 - 0.035(67) = 4.67 \text{ grams}$$

for downward acceleration. With a similar upward acceleration the stylus force would become 9.33 grams instead of the nominal 7 grams. Since a 23-in. radius of curvature is actually a rather mild condition of warp, it is clear that such considerations are by no means negligible. A "peak-to-peak" change of 4.66 grams is over 60% of the "nominal" stylus force! Clearly, stylus and record wear must be increased when the acceleration is upward; distortion and surface noise increase and tracking ability is impaired when acceleration is downward, with consequent lowering of stylus pressures. Or, if 7 grams were the minimum stylus force for proper tracking with a given pickup, under such conditions the "nominal" force would have to be increased by about 2 grams, resulting in a maximum stylus force of nearly 12 grams during upward accelerations.

Similar calculations can of course be made for lateral accelerations, but it is not felt necessary to include them here, especially since they are generally smaller, as indicated above.

In addition to utilizing higher pickup compliances to lower the equivalent mass while retaining satisfactory performance, it is also possible to decrease the equivalent mass for vertical motion while maintaining the desired value for lateral motion by hinging the arm at some convenient point. Further improvement may be effected by spring counterbalancing this hinged section rather than mass counterbalancing it, for it must be remembered that mass counterbalancing increases the moment of inertia but spring counterbalancing does not. By adopting such expedients it is possible, in a rigid arm mounting a conventional cartridge, to make the equivalent mass effective for vertical motion of the order of 25 grams, thus improving performance by a like factor (Fig. 6).

In addition to keeping the arm resonance below a given frequency for best performance, it is desirable to keep the amplitude at resonance as low as possible. Any sharp peaks, with their implication of a high-Q condition, will result in poor performance here, as in electrical circuits, because of the likelihood that even random impulses will contain some harmonics which may excite such a system. It is well known that records played through a system with over-all flat response will appear to have less surface noise than when played on a system with peaks, even if the latter system embraces a narrower range of frequencies. It may not be quite so well realized that a similar situation obtains in terms of rumble content, but that this is so was demonstrated before the New York A.E.S. on December 15, 1953. The arm whose curve is shown in the upper part of Fig. 1 was used on a conventional record changer arranged so that the arm whose curve is shown in Fig. 7 could be compared directly. In spite of the superior bass response of the better arm, the rumble content of the table appeared to be conspicuously lower.

Damping

The control of resonance amplitudes is a function of damping. All mechanical systems have some damping inherent in their construction, just as in the case of electrical

circuits. Additional damping may nevertheless be desirable, and it may therefore be of interest to examine the possibilities.

Damping may be introduced within the cartridge itself or at the arm pivot, the latter being the more common method. The usual means adopted for introducing such damping is to fill the space between a ball and socket attached to the arm with a viscous fluid, the arm being suspended by a single bearing located above the center of gravity of the system. An adjustment is ordinarily provided for increasing or decreasing the friction.

Before analyzing some of the factors relating to damping, it should be pointed out that viscous (or other) damping is not a panacea. For reasons to be partially outlined below, it is not practicable to make the damping more than a fraction of critical damping which would result in aperiodic performance.

Hence, although the resonance peak is reduced, it is not *eliminated*. The problem, therefore, of designing for a low fundamental resonance frequency still remains. Similarly, the necessity of eliminating torsional resonances is not circumvented, since it is clear that a structure which will vibrate torsionally when solidly clamped at one end will also do so when one end is only damped. Here, as in so many circumstances, what is gained in one direction is apt to result in some sacrifice in another. The final decision as to the best compromise lies, of course, with the user of such equipment, for many designs are available to his choice.

Fluid damping is widely used, for the resistance of a fluid to motion is proportional (or nearly so) to velocity, and hence it is an exact counterpart of electrical resistance. This linear relationship between velocity and resistance means that at the low velocities involved in following the record spiral very little additional friction is brought into play, but when the velocity becomes greater owing to resonance the opposing force is correspondingly increased.

This behavior, highly desirable from one point of view, is much less so when the variations in stylus pressure due to warps are considered. In the cases which we have discussed, where there was no fluid damping, variations in stylus force were due only to accelerations, for when the stylus is rising or falling at a constant rate it is in translational equilibrium. With the introduction of fluid damping (for all directions of motion), the force variations due to accelerations remain what they were without damping, but in addition there is an increase in stylus force for *constant* velocity of rise, or a decrease for a falling record surface, due to the damping action. Hence such damping action does not in any way improve the ability of the stylus to follow warped (or eccentric) records; in fact, the performance in this respect is impaired, which may perhaps be considered the price paid for lowering the amplitude at resonance by this means.

The magnitude of this effect may easily be approximated from the terminal velocity of the arm when the front of it is lifted and allowed to fall. In the case of the hypothetical arm of Fig. 5 the unbalanced force is 7 grams. Suppose that damping is now added at the pivot position. If the arm falls (at the stylus position) at the rate of 1 in. in 3 seconds the friction force as referred to the stylus position may be expressed as

$$7 \div \tfrac{1}{3} = 21 \text{ grams/in./sec}$$

Thus, if the stylus were rising at a constant rate of $\frac{1}{10}$ in./sec, the additional stylus force due to damping would be 2.1 grams, a 30% increase. If the stylus were falling at constant velocity, the force would be reduced by 30%, or to 4.9 grams. Superimposed on such stylus force changes due to damping would be any forces due to accelerations, for accelerations may occur at points along the rising or falling portions of the warp in addition to those which must occur at the beginning and end of the warp. A rise of $\frac{1}{16}$ in. in a quarter revolution is not unusual, so that changes of stylus forces of this amount may be expected in practice. The obvious implication is that with this type of damping the "nominal" stylus force must be increased to ensure proper tracking on falling slopes, with still further increases resulting on rising slopes. (Again, calculations for eccentrics are here omitted, but the same general principles will apply.)

It is possible to design an arm in which damping is active only for lateral motion, the argument being similar to that supporting the use of a hinged arm to make the dynamic mass for vertical motion smaller than that for lateral motion, and at least one such arm is now available.[2] Such a design also avoids the unfortunate tendency of arms using a ball and socket arrangement to assume a position, while playing, in which the stylus is not vertical. (Although in theory an arm suspended from above its center of gravity should come to equilibrium in the desired position, in practice this is often not so. The reason may be that the equilibrium position is actually not that in which the stylus is vertical owing to some condition of unbalance. Or it may be only that for rotation about a longitudinal axis the arm is overdamped, with a consequent sluggish return to equilibrium after the arm has been displaced from the ideal position by the act of lifting it to place it upon the record.)

Still another approach is to incorporate more low-frequency damping into the construction of the pickup itself. That such damping can have a useful effect is shown by the curves of Fig. 7. These curves represent the performance of two pickups in an arm[3] developed according to the principles outlined in this survey. For the upper curve a cartridge incorporating low-frequency damping is used, and for the lower curve a cartridge employing only high-frequency

[2] Fairchild Model 202 (Turret Arm).
[3] Fairchild Model 280, 281 Arm.

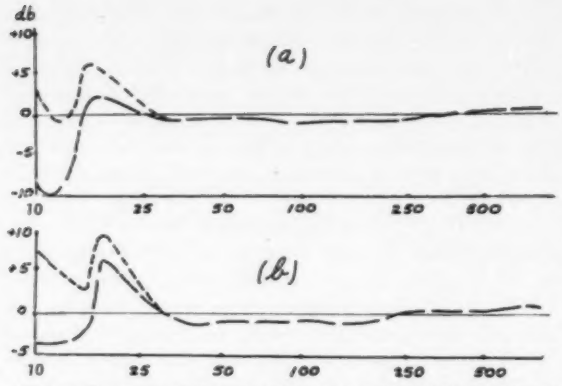

FIG. 7. Response of dynamic pickup (a) and variable reluctance pickup (b) in arm developed according to principles discussed in this paper. (Fairchild Recording Equipment Co.)

damping. As more progress is made along these lines it may be possible to dispense entirely with the need for fluid damping in the arm itself and with its attendant difficulties. At least it may be said that the required amount of damping can surely be reduced.

In Fig. 8 is shown an interesting comparison between the performances of a typical, good-quality changer arm mounting the same two cartridges as were used in Fig. 7. The greater smoothness of the upper curve, utilizing the pickup which incorporates low-frequency damping, would seem to indicate that if such an arm must be used, even greater improvement, percentage-wise, may be expected by the use of a cartridge with damping than in the case of a better arm. This does not imply that the final results will be optimum when such a light arm is used.

It may be said, then, that damping can improve a well-designed arm but it cannot make a good arm of a poor one. In any case torsional resonances should be completely absent, the fundamental resonant frequency should be low, the peak at resonance should be as low as possible, and the dynamic mass effective for arm motion, but particularly for vertical motion, should be as low as possible. These requirements for high-quality performance imply that the cartridge and arm should be considered as a unit for the best possible results. Damping action should also be held to a minimum value for vertical motion. If an arm with universal damping action is used, it should be adjusted so that stylus pressures do not exceed proper limits for good performance and long record wear.

II. TRACKING ERROR AND DISTORTION, MOUNTING OF ARMS, LATERAL STYLUS FORCES

Reference was made earlier in this discussion to the increasing precision of modern recording techniques. The degree of this precision is evident if we consider that a nominal recording velocity of 6 cm/sec means an amplitude of a little under 0.4 mil, or 0.0004 in. at 1000 cps. At 10,000 cps the amplitude of the modulation would be one-tenth this, or 0.00004 in. Since the energy in the latter region is associated only with harmonics, the change in groove shape will be only a fraction of this amount if the "average" level of the recording is the assumed 6 cm/sec. It may be seen, then, that we are dealing with mechanical precision of an extremely high order. (In the last analysis the performance of a sound reproducing system depends upon, and is limited by, the possible precision of the mechanical rather than the electrical factors.) In fact, thinking along such lines leads to the conclusion that it is not surprising that some flaws may be detected in even the best systems. It is more astonishing that such a close approach to perfection has been achieved.

In view of the foregoing statements it does not seem unreasonable to assume that great care should be taken with the mechanical aspects of the transducers at each end of the reproducing chain. In particular, we wish here to consider the effect of tracking errors on over-all performance.

Tracking Error Distortion

Figure 9 shows the tracking error of a well-designed arm, and the distortion to be expected on theoretical grounds from this error. The amplitude of modulation is assumed to be high: 0.001 in. at 1000 cps (corresponding to a peak recording velocity of 16 cm/sec), and hence the distortion is the greatest that could well be expected from tracking error alone when this arm is properly mounted. The qualification is made because the effects of improper mounting can be appreciable. To illustrate this point, the curve of Fig. 10 shows the distortion to be expected from this source

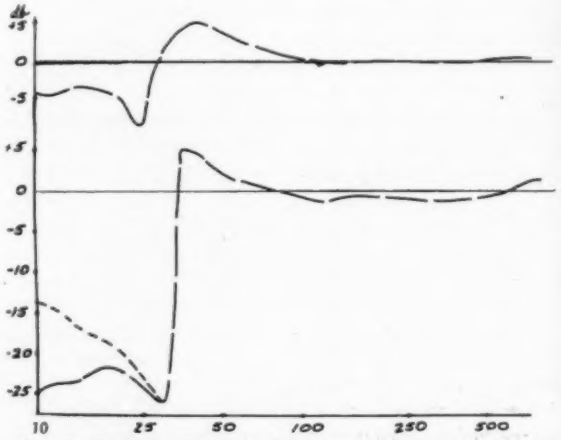

FIG. 8. Response of pickup with internal damping (above) and pickup without low-frequency damping (below) in good-quality changer arm. (Fairchild Recording Equipment Co.)

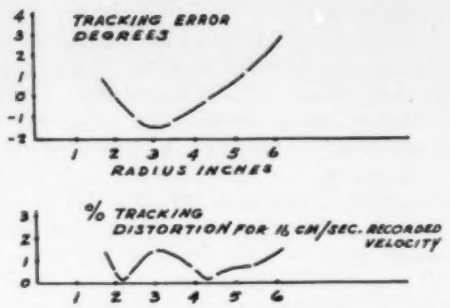

FIG. 9. Distortion due to tracking error (theoretical) for well-designed arm, correctly mounted. (Fairchild Recording Equipment Co.)

when the arm is mounted ¼-in. forward of its correct position. It would therefore seem inconsistent to insist on amplifiers with distortion far below the 1% point for almost any desired listening level, while simultaneously neglecting the adjustment of another component which may introduce distortion of many times this amount.

The distortion exhibited in these curves is only that arising from improper tracking and is based on well-established theoretical considerations. It does not take into consideration other tracing errors which may be and usually are present. There is always a distortion product, principally third harmonic, owing to the fact that a spherical stylus tracing even a perfect sine wave groove cannot, by the geometry of the situation, describe a pure simple harmonic motion. The pinch effect is neglected, as is the fact that even-order harmonics which should cancel out in lateral recordings may not do so if the stylus pressure on the two walls is unequal. Even the best cutters have some distortion, and this, too, is neglected at this point. With so many possible sources of distortion present, it would seem well worth while to eliminate all those which are within the control of the user of high-quality equipment.

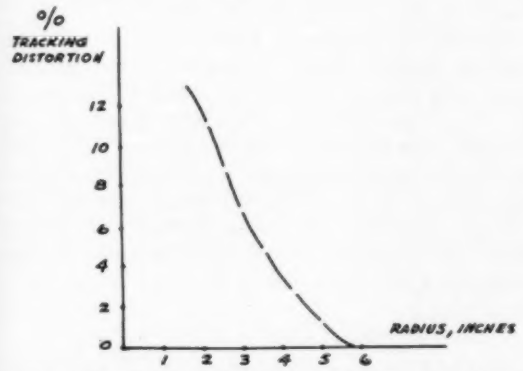

FIG. 10. Distortion (theoretical) due to moving arm forward ¼ in. (Fairchild Recording Equipment Co.)

There have been many excellent treatments in the literature of the problem of arm design, most of them being of more interest to the designer than to the user. In the following discussion it is hoped that an analysis of families of curves rather than the derivation of formulas for "optimum design" will make clear to the user the significance of these relations from his point of view, which is the mounting and adjustment of a well-designed arm rather than the manufacture of such an instrument.

Figure 11 represents a turntable with center C and an arm pivoted at P, its stylus at S. If the arm were straight there would be only one position where the tracking angle error would be zero, that is to say, where the line of symmetry of the pickup would be along a tangent to the groove. The amount of error, as the stylus traverses the record, could be made less than any specified amount by increasing the length of the arm sufficiently. This is, for practical reasons, obviously not permissible. The nearly universal

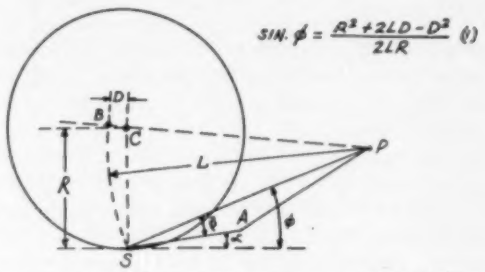

FIG. 11. Arm and turntable geometry. (Fairchild Recording Equipment Co.)

practice has consequently become to bend the arm, as shown by PAS in the figure, or to mount the pickup at an angle to the arm. Either method improves the tracking by a wide margin.

The manner in which this improvement is effected may be seen from the relation given in Fig. 11, which may be derived at once from an application of the law of cosines to triangle PCS. In Fig. 12 is shown a plot of this function for a value of 11.5 in. for L, and for three values of D, commonly referred to as the overhang. ϕ is the tracking angle error for a straight arm PS, and it may be seen that, as R increases, so does ϕ when $D = 0$, but when D has a positive value (i.e., $L > PC$) the curve passes through a minimum. Differentiation of equation 1 (Fig. 11) will show that this minimum occurs as shown by the relation in Fig. 12.

There are two effects evident at once. The first is that the curve passes through a minimum if D is greater than 0. The second is that a change of the position of P relative to C, i.e., changing D, causes ϕ to increase with increasing values of D.

The fact that the value of ϕ passes through a minimum

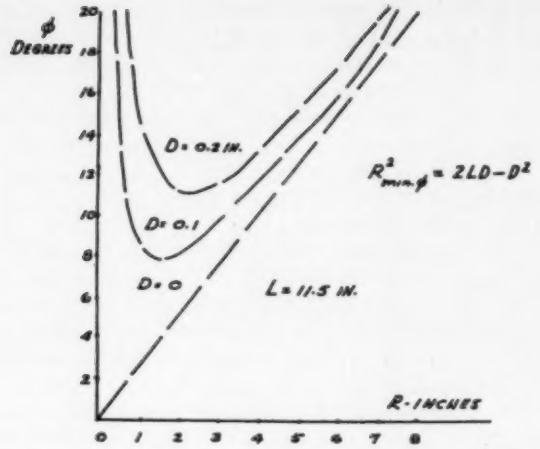

FIG. 12. Tracking error (α) *vs* radius for varying amounts of overhang (D) for straight arm. (Fairchild Recording Equipment Co.)

makes possible the improvement in tracking. For, although the angle between the tangent and the line PS is increased by increasing D, it is now possible to "bias" the cartridge by turning it through some angle β (Fig. 11) such that the actual tracking angle error is smaller. This is shown in Fig. 13, where a value of 0.45 in. has been selected for D and a "bias" angle of 18° for offsetting the cartridge. It should be noted that β refers to the angle PSA, and *not* to the angle PAS. Comparison of Fig. 13 and Fig. 12 will show the improvement due to the offset. In Fig. 12 the tracking angle error would be the value of ϕ for any of the curves given. In Fig. 13 the error is the *difference* between ϕ and β. This value is seen to be very small in comparison. The tracking angle error which remains is $\phi - \beta$, which we may call α. Not only is α smaller than ϕ, but there are two positions where α is 0, whereas only one is possible if no offset is used.

It is not alone the value of α which must be considered,

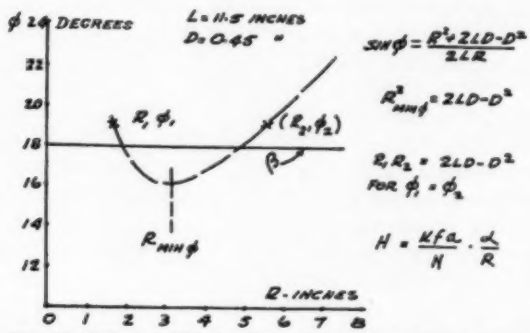

FIG. 13. Effect of "biasing" the pickup by rotating it through an angle β (see Fig. 11). (Fairchild Recording Equipment Co.)

however. The distortion (principally second harmonic) due to this angle is also a function of the recorded amplitude and frequency, and the radius of the record groove as well as of the turntable velocity. This is expressed in two forms in Fig. 14. For a given recording level and table speed it may be said that the distortion is proportional to α/R. Thus the distortion, for a given value of α, increases as the radius decreases. Furthermore, the curves of Fig. 12 or Fig. 13 may be seen to rise more steeply for small values of R than for large ones. All these facts combine to place severe restrictions on the choice of L, D, and β for best results. The curve of Fig. 15 for $D = 0.45$ in. shows the way in which α/R, and hence H (for a given recording level), varies. The simplest way of translating the curves of Fig. 15 to per cent distortion is to use the relation given in Fig. 14,

$$H = 0.5 V_R \cdot \frac{a}{R}$$

Since it is frequently true that the highest recorded level occurs at the end of a record, it will be appreciated that careful adjustment is required in order to obtain low distortion at this point.

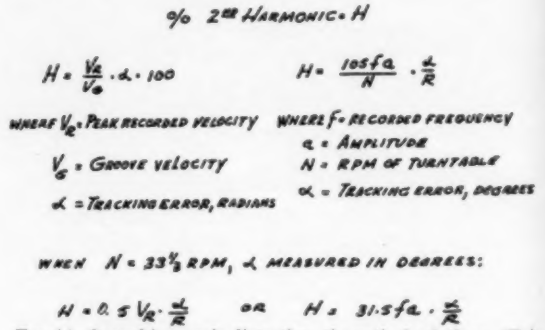
% 2ND HARMONIC = H
$H = \frac{V_R}{V_G} \cdot \alpha \cdot 100$
$H = \frac{10.5 f a}{N} \cdot \frac{\alpha}{R}$
WHERE V_R = PEAK RECORDED VELOCITY
V_G = GROOVE VELOCITY
α = TRACKING ERROR, RADIANS
WHERE f = RECORDED FREQUENCY
a = AMPLITUDE
N = RPM OF TURNTABLE
α = TRACKING ERROR, DEGREES
WHEN N = 33⅓ RPM, α MEASURED IN DEGREES:
$H = 0.5 V_R \cdot \frac{\alpha}{R}$ OR $H = 31.5 f a \cdot \frac{\alpha}{R}$

FIG. 14. Second-harmonic distortion, theoretical relations. (Fairchild Recording Equipment Co.)

It should also be borne in mind that recordings are *not* made at constant velocity, in most cases, except for a rather small part of the frequency spectrum. Constant amplitude is used below the turnover frequency, and pre-emphasis at the high-frequency end will cause the recording characteristic to approach more nearly constant amplitude than constant velocity. If pre-emphasis were at the rate of 6 db/octave we should have constant amplitude recording, and the other relation shown in Fig. 14 would more nearly apply. That is, in such a case

$$H = kf \cdot \frac{a}{R}$$

where f is the frequency and k is a constant depending on the other factors given, namely the level and the turntable

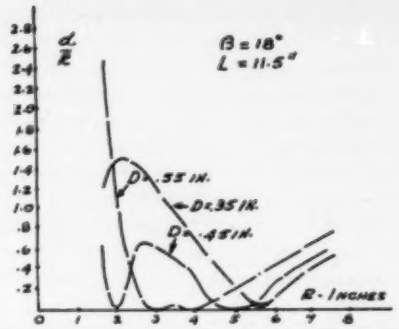

FIG. 15. Changes in distortion factor α/R associated with changes in D (Fig. 16). (Fairchild Recording Equipment Co.)

velocity. It is quite reasonable to conclude that in such a case the distortion of high frequencies would become severe, being as usual more evident in terms of spurious and inharmonic combination tones lying within the middle frequency region than in the actual harmonics themselves.

Effect on Performance of Improper Mounting

With these facts in mind it may be instructive to consider the effect of varying D by increments of 0.1 in., that is, to consider the effect of improper placement of the arm with respect to the turntable. Assuming the situation shown in Fig. 13 to represent the design of a satisfactory arm for playing records of 1.75- to 7.5-in. radius, the value of β is of course built into the arm itself. The manufacturer's specifications give the proper overhang as 0.45 in. The results will be shown by the appropriate curve ($D = 0.45$ in.) in Fig. 15.

Figure 16 shows ϕ plotted against R for the same arm with two other values of D. The upper curve represents a mounting position such that the stylus is 0.1 in. farther ahead of the turntable center than required, and the lower curve one in which the arm is placed too far back by the same amount. The tracking angle error α will be obtained by

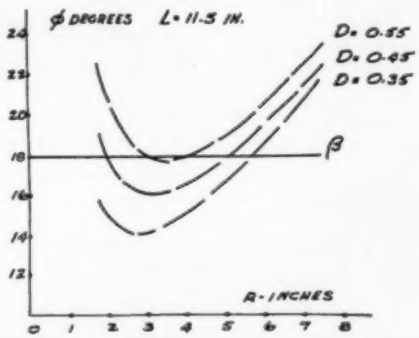

FIG. 16. Changes in tracking error due to changes in overhang (D). (Fairchild Recording Equipment Co.)

subtracting the ordinates of any of these curves from the fixed value of β. It can clearly be seen that in the case where $D = 0.35$ the value of α is zero at only one point, since the curve has been lowered too much. The value of α is increased, and so is α/R. Hence the corresponding curve of Fig. 15 shows only one zero value for distortion due to tracking angle error and distortion at other points is much greater.

In the upper curve of Fig. 16 the two $\alpha = 0$ positions have been moved closer together, with a resulting increase in distortion which is not so significant at the outer grooves as at the inner ones. Below about a 2.9-in. radius the distortion rises very rapidly, as may be seen in Fig. 15. (It should here be emphasized that the figures given in this illustration are chosen for simplicity in the discussion and are not intended to represent the best possible choice of parameters

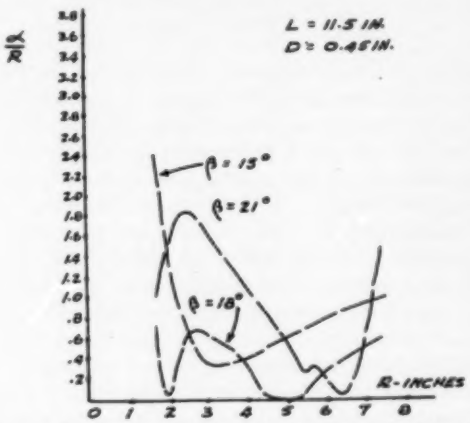

FIG. 17. Changes in α/R due to 3° misalignment of cartridge. (Fairchild Recording Equipment Co.)

for an arm of this length. The figures are near the proper value, however, and the general relationships expressed are very similar to those which obtain in a practical arm. The curves of a well-designed arm are given in Fig. 7, for comparison.)

The second way in which the user can invalidate the performance built into a well-designed arm is to mount the pickup at an improper angle. The effect of this may easily be seen by referring again to Fig. 13. If the cartridge is mounted with an error of 3°, which is quite easy to do because of the size of the clearance holes in cartridges as related to the size of the mounting screws, β will change in this hypothetical arm from 18° to 15° or to 21°. To find the effect on the tracking angle error of such a change, all that is required is to draw a line parallel to the one in Fig. 13, but passing through $\phi = 15°$ or $\phi = 21°$. It is again evident that in one case ($\phi = 15°$) there will be *no* intersection with the curve, whereas in the other case there will

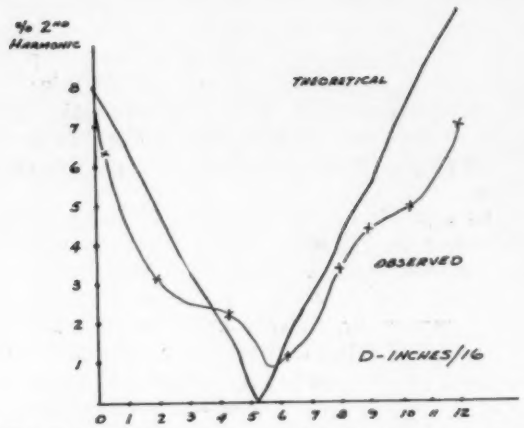

FIG. 18. Calculated and observed distortion due to changes in overhang (D). (Fairchild Recording Equipment Co.)

be only one intersection giving zero tracking angle error. In both cases distortion is significantly increased, as shown in Fig. 17. Although these conclusions may seem surprising, they really should not be so in view of the precision required in all other parts of the recording and reproducing process, as mentioned before. For the best possible results, great care is also required in the matter of arm placement, just as it is in all other phases of design and application of the components making up the complete reproducing system.

An attempt was made to verify the distortion at high levels by actual measurement, and the results are presented in Fig. 18. Numerous difficulties were encountered in making these measurements, not the least of which is the fact that records containing no distortion at about a 15-cm level are hard to obtain. Some distortion is also present in the pickup itself, of course, and the attempt must be made to separate these factors from the distortion introduced by mistracking. The method employed was to attempt to find if there were a constant relationship in the phase angle between the inherent distortion and that due to tracking error. By comparison at several points of many curves, it was found that the difference seemed to be quite close to 90°, and the appropriate correction was applied on this assumption. The observed curve does not fit the theoretical one precisely, but it does follow it in general, and does so closely enough to indicate that the predictions of theory should not be neglected in practice. It is hoped that further measurements may be made when better recordings can be obtained at these levels.

One interesting agreement with theory is the observed result that the amount of third harmonic distortion varied practically not at all with pickup placement. Theory shows that the distortion should be chiefly second harmonic, owing to tracking angle error, and this was found to be true. Fourth harmonic distortion was also present and followed roughly the same pattern as second, although in very much smaller amounts.

The foregoing has been referred to the usual sine wave analysis, but since music (and speech also) contains many transients, it may be worth while considering briefly the effect of tracking angle error on the response of a velocity-sensitive pickup to a wave front rather than to a steady-state tone. In Fig. 19, OX represents the direction of the unmodulated groove, traveling to the left as indicated. OA represents a wave front approaching the stylus which is at O initially, and which would, if α were zero, travel along the line OY as the wave front moved past it. If the error angle is α, the stylus will be constrained to move along OS (except for longitudinal compliance, which is here neglected). Consequently, as outlined in Fig. 19, it may be seen that the output voltage is affected by two factors. The first of these is comparatively unimportant (that is, $1/\cos\alpha$), since α is probably never greater than about 10°, which would make $\cos\alpha$ roughly 0.98 with an error in output voltage of about 2%. The second factor is quite important, however, since the denominator can theoretically approach zero with a consequent value of E_2 which would be infinitely large. This would occur, as may be seen from the diagram, if θ were the complement of α; that is, if OA were to fall along OS the time available for the stylus excursion would be zero and the output voltage infinite. If α were 5°, for example, and θ were 30°, then $1/(1-\tan\alpha\tan\theta)$ would be approximately 1.05. But if θ became 45°, this factor would become about 1.1, emphasizing the importance of the slope of the transient. Suppose that by careless mounting of ¼ in. the value of α becomes 7° at a 2.5-in. radius, and that the misalignment of the pickup is 3°, increasing α to 10°, which is quite possible. In such a case, for a slope of 45°

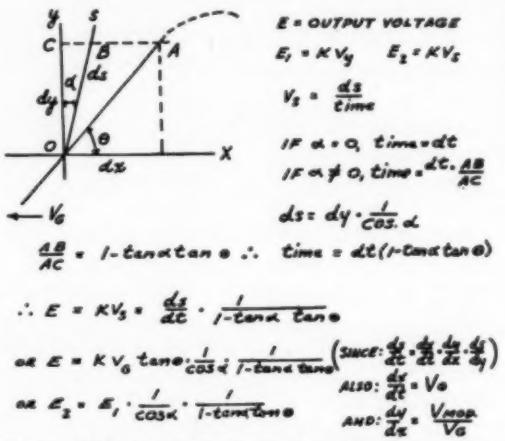
E = OUTPUT VOLTAGE
E1 = KVy E2 = KVs
Vs = ds/time
IF α = 0, time = dt
IF α ≠ 0, time = dt · AB/AC
ds = dy · 1/cos α
AB/AC = 1 - tan α tan θ ∴ time = dt(1 - tan α tan θ)
∴ E = KVs = ds/dt · 1/(1 - tan α tan θ)
or E = KV0 tan θ · 1/cos α · 1/(1 - tan α tan θ) (SINCE: ds/dt = ds/dt · dx/dx · dy/dy)
or E2 = E1 · 1/cos α · 1/(1 - tan α tan θ) ALSO: dx/dt = V0 AND: dy/dx = Vmod/V0

FIG. 19. Effect in output voltage of tracking error angle (α). (Fairchild Recording Equipment Co.)

the product of the two correction factors would be 1.23, or a 23% increase.

When the slope is negative a different condition obtains. That is, the denominator does not approach zero and hence the effect is unsymmetrical. For the same values of α and θ, i.e., 10° and 45° just assumed, but for a negative value of θ, the (total) correction factor becomes about 0.85, or a decrease of 15%. Hence, as the steepness of the wave front increases, the distortion increases, and in an unsymmetrical fashion as the slope varies from positive to negative. Other factors being equal, wave fronts will be steeper at the inner radii, once again emphasizing the importance of securing the best tracking possible from design and installation of the arm.

Lateral Stylus Forces

We have seen that tracking angle error can be reduced by offsetting the pickup. There is another effect which may not be so reduced, and this is the tendency of the arm to move inward while following the groove. Figure 20 shows the primary forces in the horizontal plane. As the record revolves, the frictional force F_{fr} acts on the stylus along the tangent to the groove. This must be counterbalanced by the pivot reaction, and, although the arm is bent, since it is pivoted at P this force must act along the line PS, denoted here by F_p. The component of this acting along the tangent, or F, must equal F_{fr}. The other component is then along the radius, called here F_c. It may be seen that the amount of this component is F_{fr} tan ϕ, where ϕ is the tracking angle error which would exist with an arm of the same length if it were not offset. The force F_c tends to make the arm "skate" toward the center of the record, and it is often thought that this effect is associated with the bend in the arm. This is not true, as may be seen from the diagram, but the fact is that a very short arm requires a rather large offset angle, since ϕ is greater for a short arm, and hence short and light arms with a very obvious bend will show a bad tendency to skate.

The importance of the side thrust is twofold. As implied

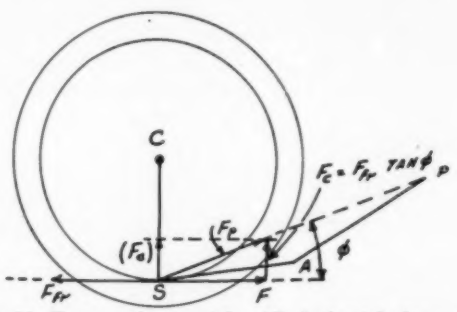

FIG. 20. Forces acting on stylus (S), horizontal plane. (Fairchild Recording Equipment Co.)

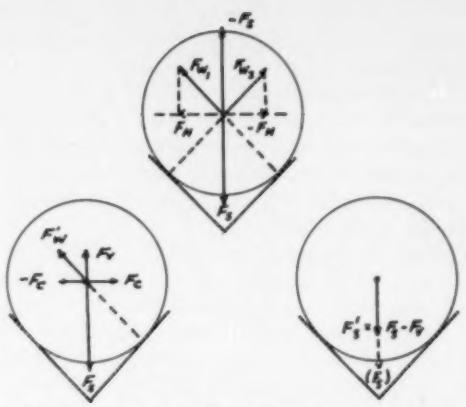

FIG. 21. Forces acting on stylus, vertical plane (cross section of groove). (Fairchild Recording Equipment Co.)

earlier, an unequal pressure on the opposite walls of the groove tends to increase even-order harmonic distortion which is normally canceled out by the "push-pull" effect obtained in lateral recording. This effect may not be very large, since the forces in question would be of the order of 0.5 to 2 grams, whereas the side thrust on the walls may be many times this, owing to acceleration forces. It is a real effect, however, because many tests of stylus wear show that the inner surface of the stylus wears faster than the outer one. Inspection of discarded styli shows the same result, indicating that it is also generally true under customary conditions of use.

The second effect resulting from the side thrust is the tendency of the stylus to ride up the wall of the groove, owing to the upward component of this force. In Fig. 21 we see a diagram of a cross section of a groove with a 90° angle and of the spherical tip of the stylus in ideal contact with it. In the top diagram, where F_s is the unbalanced downward force of the stylus, the reaction of the two walls must be along lines perpendicular to the walls, shown as the vectors F_{w_1} and F_{w_2}. The vertical resultant of these forces will be equal and opposite to F_s, or $-F_s$ as shown, and the horizontal components will be F_h and its opposite, producing a condition of equilibrium.

In the lower left figure we omit the original static forces (except F_s, which is left for reference) and consider the force F_c due to the angle ϕ as discussed above. This force must be opposed by an equal and opposite force $-F_c$, which is the component in the horizontal direction of the wall reaction F_w'. If the groove angle is the usual 90°, the accompanying vertical component will be F_v, which will be equal in magnitude with F_c. Hence, under such conditions the stylus force will actually be reduced by the amount of the side thrust, leaving us F_s' as shown in the third figure for the actual downward force.

The result of this condition is that the nominal stylus force must be increased for proper tracking, but since ø may vary considerably, so may the net stylus force due to this cause. It is therefore desirable from this point of view to use as long an arm as convenient, giving a smaller value of side thrust as well as less variation. Allowing a small amount of residual friction in the vertical pivots can also reduce this effect, but it cannot be completely balanced out at all points of the record.

Returning to the numerical example quoted on p. 154, let us now add the effect of the centripetal thrust. We may reasonably assume a value for ø of 20°, and of the coefficient of friction between stylus and groove of 0.33. Then, if the net downward force has been reduced to 4.67 grams because of accelerations required to follow the groove,

$$F_{cr} = F_s \mu \tan 20° = 4.67\ (0.33)\,(0.364)$$

or

$$F_c = F_c = 0.56 \text{ gram}$$

The remaining stylus force is then 4.67 – 0.56 gram or 4.11 grams, which may not be enough for proper tracking with many pickups, for even if the dynamic mass of the stylus assembly is reduced to milligrams, accelerations of 200*g* and upward will require a side force of several grams, and, as before, the vertical component of this force will be equal in magnitude.

A comparison with an arm of 25-gram dynamic mass in the vertical direction would show that, for the same conditions, $F_s = 7 - (0.035)\,(25) = 6.12$ grams instead of 4.67. The reduction of F_s due to centripetal force is increased slightly, since the stylus force is greater. Then

$$F_c = 6.12\ (0.33)\,(\tan 20°) = 0.73 \text{ gram}$$

Hence

$$F_s = 6.12 - 0.73 = 5.39 \text{ grams}$$

representing an over-all improvement under these conditions of about 30%. Where warps have a greater acceleration rate, the improvement would be even more noticeable. For example, for half the warp radius of curvature (twice the acceleration) the 67-gram arm would give a stylus force of 2.03 grams. The 25-gram arm would give 4.62 grams, an improvement of about 125%.

The problems involved in the design of arms are not simple, but a fairly good compromise can be worked out. It is the responsibility of the user of carefully designed arms to see that their actual performance is equal to their potential. It is hoped that the points brought out in this survey may aid the users of such equipment to make an intelligent choice of arms and pickups to be used with them, and that a wider general understanding of the relationship of design considerations to careful installation may help in furthering the general advance of the art of sound reproduction.

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The Fundamentals of Disk Reproduction*

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Cosmocord, Ltd.

THIS DISSERTATION deals only with essential mechanics for reproduction from disk. In particular, it will be confined to so-called long-playing disks, although much of what follows will be applicable to standard 78 rpm disks.

RECORD REQUIREMENTS

It is assumed that the disk will be produced in accordance with British Standard 1928, and that the design centers for groove profile and reproducing stylus shall be used. It may not be inappropriate to mention that the British Standard (1928) specifies groove width of 0.002 to 0.003 in., whereas the Americans specify 0.0027 to 0.003 in. Limits for the reproducing stylus are ± 0.0002 in. for the British and $+0.0001$ to -0.0002 in. for the American. These limits are extremely important when one considers high modulation levels and maximum playing times. With the bottom limit of 0.002 in. for groove width and a top limit of 0.0012 in. for stylus radius, pinch effect limits maximum modulation at high frequencies. However, some American-produced records claim playing times in excess of 30 minutes; they (the Americans) must either be using elastic disks or working with groove widths considerably less than their stated standard. In general, the British Standard specification is more nearly in keeping with accepted practice today, although in a few cases groove widths as low as 0.0017 in. have been noted.

The foregoing facts have been stated because the intelligent design of reproducers is very intimately connected with the physical constants of the disk. A further assumption will be made that, if the reproducing chain, i.e., the pickup, equalizing network, and amplifier, are so arranged to give a constant output voltage when driven by a disk cut to the alleged recording characteristics produced by the recording company, the tonal balance of the reproduced music will be the same (when played on an identical speaker) as heard by the recording engineer, and this, in an imperfect world, is the utmost we can expect.

Most British recordings are produced on a variable pitch system in order to obtain maximum playing time for a given maximum recording level. The maximum amplitude at the low-frequency end is approximately 0.01 cm, and the maximum velocity at the high-frequency end is about 45 cm/sec.

The record behaves essentially as a constant velocity generator with a compliance across the output terminals. This is equivalent to a constant current generator in parallel with a capacitance, and it is this compliance, together with the effective mass of the stylus tip, which is generally responsible for the high-frequency resonance exhibited by most pickups. The value of this compliance is about 1.5×10^{-6} cm/dyne for shellac 78-rpm records, and 2.5×10^{-6} cm/dyne for Vinyl long-playing records. The above values were obtained with cantilever-mounted styli with radii of 0.0025 in. for standard and 0.001 in. for long-playing and were

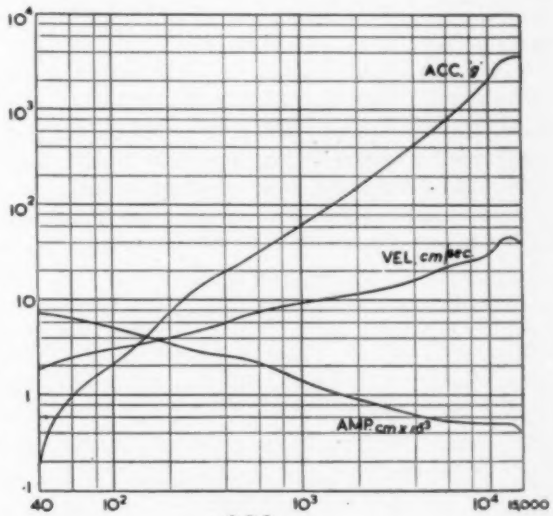

FIG. 1

* Paper read before the Association of the Royal Society of Arts, October 23, 1953. Reprinted from *Sound Recording and Reproduction*, 4, 91-99 (January, 1954).

measured by using a resonance system with an effective mass of 10 mg.

Figure 1 shows the recording characteristics of a British long-playing disk, as taken from Decca LXT 2695 and then equated for maximum possible recording levels. The velocity curve follows an average slope of approximately 3 db per octave, but it is worth while noting that at frequencies between 7 kc and 12 kc the slope is almost 6 db per octave. In other words, it is cut on a constant amplitude basis.

The high-frequency pre-emphasis on present British records is considerably less than on the American. This is extremely important in view of the maximum acceleration at high frequencies to which the stylus tip can be subjected. Nontracking at these high frequencies can result in a very insidious form of distortion, which in the writer's opinion is one reason why the high-frequency distortion of some LP pressings is so bad; in a number of cases investigated the pre-emphasis at 10 kc was about +16 db referred to a 1-kc level. In modern symphonic music, the peak power is radiated in approximately two main frequency bands: the low-frequency band covering up to 500 cps, and the high-frequency band, 8 kc to 11 kc; and from a total peak power of approximately 60 acoustic watts, the bass drum radiates about 24 watts in the low-frequency region, and the cymbals radiate 10 watts in the 8-kc to 11-kc region. The total power above 11 kc decreases very rapidly, and for practical design purposes 10 kc can usually be taken as the upper frequency limit for maximum modulation. This maximum velocity is approximately 32 cm/sec and corresponds to an acceleration of about $2000g$. When it is realized that the effective mass of the stylus tip is increased by 2000 times at this frequency, the necessity for very low effective mass referred to the stylus tip becomes apparent.

At the low-frequency end of the scale, the displacement is the controlling factor, and the maximum value is approximately 0.008 to 0.01 cm. The value of this displacement, together with the vertical stylus force, determines the minimum working compliance of the reproducer system.

Assume that the stylus moves laterally with a sinusoidal motion of peak displacement, X, and frequency, f. Then

$$x = X \sin 2\pi ft \tag{1}$$

where x = displacement at time t.

$$V_h = \frac{dx}{dt} = 2\pi fX \cos 2\pi ft \tag{2}$$

$$a = \frac{dV_h}{dt} = -(2\pi f)^2 X \sin 2\pi ft \tag{3}$$

From equation 2,

$$\text{Peak velocity} = 2\pi fX \tag{4}$$

and from equation 3,

$$\text{Peak acceleration} = 4\pi^2 f^2 X \tag{5}$$

Assume that X = cm; then V_h = cm/sec, and a = cm/sec^2.

g = the acceleration due to gravity = 981 cm/sec^2

and

$$G = \frac{a}{g} \tag{6}$$

Then from equations 5 and 6,

$$G = \frac{4\pi^2 f^2 x}{981} = \frac{f^2 x}{25} \tag{7}$$

From equations 4 and 5,

$$a = 2\pi fV_h$$

$$\therefore\ G = \frac{2\pi fV_h}{981} = \frac{fV_h}{156} \tag{8}$$

As is well known, pinch effect becomes increasingly serious at high frequencies, especially when the recorded velocity is high and the linear velocity of the groove past the stylus tip is small, i.e., toward the center of the disk. This pinch effect results in a vertical velocity being imparted to the stylus point at twice the lateral frequency. Fleming[1] has found the vertical velocity to be given by:

$$V_v = 0.35\, R\omega \frac{(V_h)^2}{(V_g)^2} \tag{9}$$

where R = radius of the stylus tip.
V_h = vibration velocity.
V_g = linear velocity of the groove, reference the stylus tip.

It will be apparent that this vertical velocity is directly proportional to frequency and varies as the square of the ratio of the vibrational velocity to the linear velocity. In practice, this means that the pinch effect will become serious

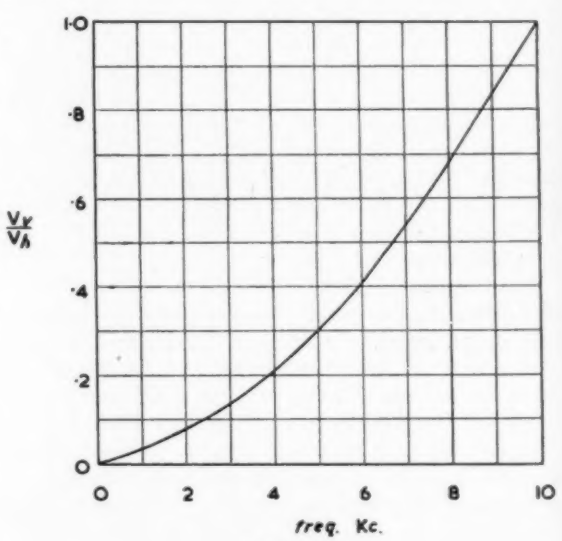

FIG. 2

[1] John G. Frayne and Halley Wolfe, *Elements of Sound Recording*, p. 251, John Wiley and Sons, New York, 1950.

toward the center of the disk, especially with high modulation levels of the high frequencies.

The groove velocity has been assumed at 42 cm/sec for a diameter of 12 cm at 33⅓ rpm, and equation 9 then simplifies to

$$V_h = 3.16 f V_h^2$$

where f is in kilocycles. Figure 2 shows the relationship between vertical and horizontal velocities for a long-playing record cut in accordance with the characteristics of Fig. 1. Thus, at 10 kc the lateral and vertical velocities are approximately the same, and at higher frequencies the vertical velocity could actually exceed the lateral velocity. This ratio is credible when it is remembered that the radius of the stylus tip is considerably greater than the wavelength of a 14-kc trace at these low groove velocities.

The result of the pinch effect is threefold. If the mass and area of the moving system in the vertical direction are large, as in the case of pickups with low vertical compliance (and quite a number of cartridges have been measured in which the vertical compliance was less than 1/100 of the lateral compliance), the whole pickup head will tend to vibrate vertically; and since, according to basic physics, action and reaction are equal and opposite, the disk will tend to vibrate in a horizontal plane, because the two masses are coupled by a 45° plane. Thus considerable radiation of acoustic energy will take place at double the lateral modulation frequency. It is this second-harmonic radiation that gives rise to the distressing needle chatter heard on some pickups but which can, of course, be reduced by using the pickup in a well-constructed soundproof box.

The second effect is more important: that is, increased record and stylus wear (due to the high mechanical impedance at the stylus tip in a vertical direction) when subjected to these high accelerations. Finally, some pickups have an appreciable vertical response, and the result of this pinch effect will be to convert the pickup into a very effective generator of second-harmonic distortion.

Tracing distortion also raises its ugly head. This, however, is a function of the geometry of the record design, and there is nothing that the pickup designer can do to reduce it below present levels. It will therefore not be discussed.

To summarize, we are provided with the following design data by the record manufacturer, which is completely out of the control of the pickup designer, and around which he must build his transducer design:

1. Minimum groove width of 0.002 in. and included angle 90°.
2. Maximum displacement at 40 cps of 0.010 cm.
3. Maximum velocity at 10 kc of 31 cm/sec.
4. Maximum recorded frequency of 15 kc.
5. Record compliance of 2.5×10^{-8} cm/dyne.

BASIC PICKUP DESIGN

The record groove walls are normally assumed to have an included angle of 90°, and the stylus tip is spherical in shape. The lateral undulations of the groove will result in relative lateral motion of the stylus (provided that the downward vertical force is greater than the lateral force). It can be shown that the maximum lateral force exerted on the stylus is equal to the maximum displacement divided by the compliance of the stylus system. If the vertical force due to the weight of the pickup head is less than the horizontal force due to the relative motion of the record groove, the stylus will tend to ride up one or another of the walls of the groove. The minimum weight required to keep the stylus in the groove will be equal to the maximum displacement in centimeters divided by 981 times the stylus compliance,

Figure 3 shows the ratio of stylus force against mechanical impedance, assuming the levels shown in Fig. 1. For any other maximum velocity, a different curve would obviously be required. The successful tracing of any record is controlled by three, and only three, factors: the impedance of the stylus tip, the recorded velocity, and the vertical "stylus force." Now may be an opportune time to digress on a definition of stylus force.

Reading current literature and manufacturers' catalogues, one sees such terms as "needle pressure 2 oz," "stylus force 20 g," "tracking weight ½ oz" (and several other terms), all presuming to denote the same thing. What is physically happening, of course, is that a vertical downward force due to gravity and the effective mass of the pickup is applied to the stylus, and "needle" or "stylus" force would therefore appear to be the academic definition. "Force" is used in many other concepts, however, and the writer prefers the term "playing weight," because this denotes, in a practical way, what the engineer measures. In other words, a "play-

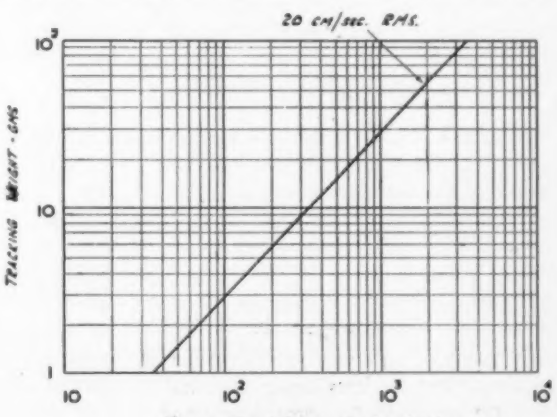

FIG. 3

ing weight" of 10 g is exactly equivalent to a "stylus force" of 10 g, or, if you wish, 10^4 dynes. The correct conception of playing weight becomes important in relation to counterbalanced arms (either by counterweight or spring) in calculating the low-frequency resonance, which is a function of the effective lateral mass of the pickup, and the compliance of the moving system (armature, etc.).

If we take the simplest mechanical system used in any pickup, comprising a rigid armature with a stylus at one end, a restoring means, and a bearing, it will behave as a simple series resonant circuit, in which the effective mass of the stylus will resonate with the stiffness (reciprocal of compliance) of the restoring medium. We can obviously choose any values we wish, but the final playing weight of the pickup will be determined by the compliance and displacement at the low-frequency end and the mass and acceleration at the highest frequencies. The minimum compliance is given by

$$C_{ms} = \frac{X}{F} = \frac{X}{981\,P_w}$$

where X = displacement in cm.
F = force in dynes.
P_w = playing weight in g.

This, for a playing weight of 10 g, will give a value of 10^{-6} cm/dyne. In practice, this value must be increased by at least times 2 in order to allow a factor of safety, and it is also assumed that the effective lateral mass of the pickup and tone arm will resonate with this compliance at a frequency lower than the lowest recorded frequency. Should the low-frequency resonance occur in the recorded band, the stylus tip impedance will rise at the resonant frequency. This will require an increase in playing weight by the same ratio to keep the stylus in contact with the groove walls.

The maximum effective mass of the armature is given by

$$M = \frac{P_w}{g}$$

where M = effective armature mass.
g = acceleration of stylus tip.

This gives a value of 5 mg for a playing weight of 10 g at 10 kc. Taking these two values of mass and compliance and applying the usual formula for series resonance gives a frequency at which the impedance is minimum. It has been experimentally determined that this resonance should not be greater than about 1 kc in order that the maximum mechanical impedance shall be approximately equal at both ends of the frequency spectrum.

Mechanical impedance is defined as the ratio force/velocity; therefore, knowing our maximum recorded velocity and the usable stylus force determined by the playing weight, we can specify the maximum mechanical impedance

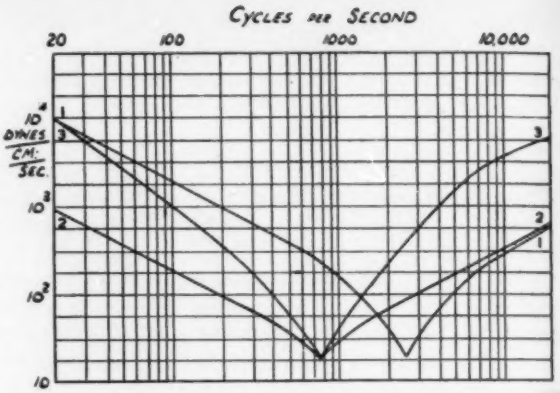

FIG. 4

of the system for adequate groove tracing. This, for long-playing records at 10 g, is approximately 300 mechanical ohms.

The effect of varying mass and compliance is shown in Fig. 4. Curve 1 shows a low-compliance, low-mass system. The low mass is satisfactory for high-frequency tracing, but the unit will not be satisfactory at frequencies below 600 cps because of the excessive stiffness. It is seen that the resonant frequency is approximately 2500 cps, which is well above the maximum.

Curve 2 shows the effect of increasing the compliance by times 10 but still leaving the effective mass as in curve 1. This pickup will obviously be satisfactory over the greater part of the frequency range. Its resonance is at 750 cps, well below the danger point.

Curve 3 shows the effect of bringing the resonant frequency down by increasing the mass instead of increasing the compliance. Very little is gained in the low-frequency end, but the impedance rises enormously at the high-frequency end of the band. In this case, the compliance is as in curve 1, with the mass increased by times 10.

In the above example we have assumed an ideal system, with infinite tone arm mass and zero record compliance. In practice we find the record behaves as a constant current generator in parallel with a compliance; the value of this compliance on Vinyl records is about 2.5×10^{-8} cm/dyne, and this will resonate with the effective stylus mass at some high frequency giving rise to the so-called stylus resonance. At the resonant frequency, the mechanical impedance of the system will rise by a ratio determined by the Q of the system, which is usually of the order of 4 to 10. Should this resonant frequency occur below 10 kc, tracing difficulties will usually be experienced owing to the high stylus tip impedance in this frequency band, together with coloration of scratch and accentuation of response at that frequency; and if it is desired to move the resonance outside this band, the only

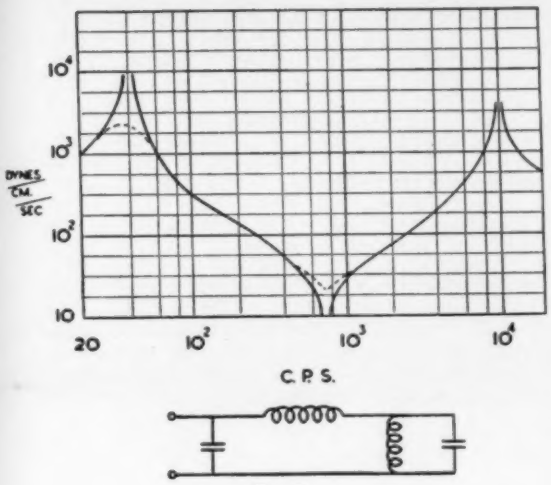

FIG. 5

solution is to reduce the armature mass. There is nothing that the pickup designer can do about the record compliance!

Until now, we have dealt only with the armature mass and have taken the mass of the rest of the system on trust. The effective lateral mass of the tone arm and pickup head may be anywhere between 10 and 60 g, and this mass will resonate with the armature compliance at some low frequency; it is the aim of the pickup designer to put this as low as possible, preferably outside the recorded range.

Figure 5 shows the mechanical impedance of a typical system. It will be seen that the low-frequency resonance has been put at 40 cps. This is much too high for modern reproducers and should normally be at 20 cps. Unfortunately, we could not show the impedance rise at this low frequency on the graph, so we have degraded the performance of the pickup under the excuse of artistic license. It will be seen that, if the effective mass of the tone arm is increased from 8 g to 32 g, the resonance will come at the right frequency, i.e., 20 cps, and it is standard practice nowadays to make the effective mass of the pickup system between 30 and 40 g. We must, however, be careful that the resonant frequency does not sit very close to 22½ cps, which is the rumble frequency of most of the domestic turntables. This rumble frequency consists of a 22½-cps vertical elliptical motion, rotating about its vertical axis at an indeterminate speed, and with appreciable lateral content; the low-frequency Q of the pickup is usually 2 to 5 (and sometimes up to 25), and with a healthy loudspeaker bass response the rumble can sound as of not too distant thunder.

By the judicious application of some form of damping to the tone arm back bearing, the effective Q, and hence the mechanical impedance, at the resonant frequency can be considerably reduced; and it cannot be emphasized too strongly that any appreciable resonance in the low-frequency band will increase the mechanical impedance by approximately the same ratio as the resonant rise in output voltage, and will decrease the tracking efficiency by that amount. In other words, if the resonant rise in voltage is times 2, the playing weight required to keep the stylus in the groove has also risen by about times 2. At the high-frequency end, the effective armature mass will resonate with the record compliance, and if adequate damping is not applied, the rise in stylus tip impedance can quite easily be times 8 or 10. In Fig. 5, this is shown at 10 kc, and if it is desired to increase the frequency of this resonance the effective mass at the stylus tip must be reduced. Referring to the circuit schematic, the mechanical input from the record is at the left, and the record compliance is shown as a capacity across the input. The series inductance is the armature mass, the parallel inductance is the total tone arm and pickup mass, and the capacity across it is the armature restoring means.

A pickup design, in accordance with the above philosophy, will suffer from one major defect. If the armature mass (either magnetic or crystal) is reduced to sufficiently small proportions to put the upper resonance outside the recorded band, the sensitivity of the pickup will suffer, and in the case of magnetic units, possible distortion due to saturation of the armature may occur if an attempt is made to restore the sensitivity by increasing the magnetic flux. One compromise is to decouple the main moving system (armature or moving coil or crystal) from the stylus tip by means of a cantilever. Figure 6 shows the effect of this. Here, two extra resonances are introduced, a parallel resonance at 2500 cps and a series resonance at 6 kc. The stylus tip resonance has now been pushed to approximately 15 kc, and the over-all effect is to reduce considerably the impedance in the high-frequency region. It should be noted that the 15-kc resonance is the stylus mass resonating with the record and cantilever arm compliances in series; the 6-kc resonance

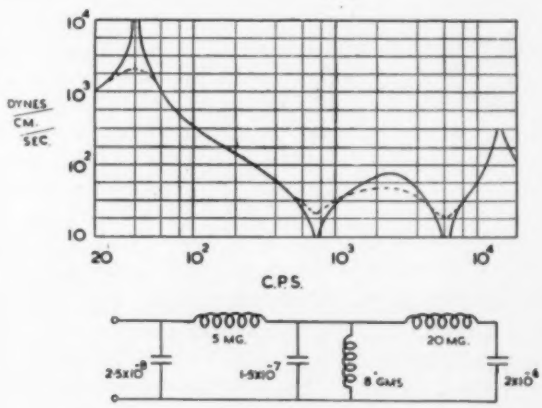

FIG. 6

is the stylus mass resonating with the cantilever arm compliance; that at 2500 cps is the armature mass resonating with the cantilever arm and restoring means compliances in series; the 700-cps resonance is the armature mass resonating with the restoring means compliance; and, finally, the 40-cps resonance is the tone arm mass resonating with all the compliances in parallel. It should be noted (but it is quite fortuitous) that the compliance increases by the order of approximately 10 to 1 at each stage.

The benefits derived from a cantilever stylus are not confined to the reduction of lateral stylus tip impedance at the high frequencies. The total effective mass of the cantilever proper is usually very much smaller than the armature system. Its surface area (which acts as an acoustic radiating system) is very small, so the needle talk is effectively reduced when compared with a rigid stylus-cum-armature system. Additionally, the vertical compliance can be increased to a value which will efficiently decouple the rest of the system from the vertical undulations due to pinch effect. The design of the cantilever, however, must be a judicious compromise between low mass and high compliance (low effective mass usually necessitates a short cantilever, and high compliance requires the reverse). If the length is excessive, the unit will behave as a low-pass filter. The limiting length is given by

$$L = \sqrt{\frac{a}{10f}\sqrt{\frac{Q}{P}}}$$

where L = length of cantilever.
f = highest recorded frequency.
Q = Young's modulus.
P = density.
a = width of cantilever.

PRACTICAL PICKUPS

Figure 7 shows a basic design that is probably the earliest and most widely used in commercial pickups. The armature is pivoted on the bottom pole, and the far end is clamped between the top poles with rubber or like material. The restoring means, C_{M_3}, usually referred to as the damping blocks, are applied to prevent the armature from sticking to one or other of the pole faces, and the stronger the magnet, the stiffer must be these rubber blocks for a given gap. The armature is usually a hefty affair resonating with the record compliance at 3 or 4 kc, and because of inherently high stiffness of the damping blocks, even with effective tone arm masses of 70 g, the low-frequency resonance is between 70 and 150 cps. The generated voltage is

$$E = \frac{NMv}{a^2 10^8}$$

where E = volts.

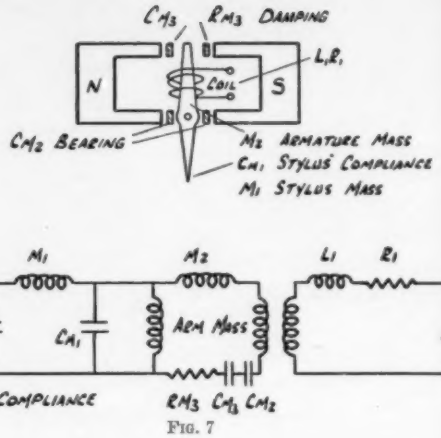

FIG. 7

N = turns.
M = magnetomotive force (effective in gap).
v = velocity of armature tip in gap.
a = gap between armature and pole.

It will be seen that the generated voltage is directly proportional to the turns, the effective flux in the gap, and the velocity of the armature tip; and it is inversely proportional to the square of the gap length between the armature and the pole piece. The velocity is fixed by the record and armature length. The number of turns is determined by the electrical load impedance; for high impedance pickups, usually about 5000 turns, dc resistance 2000 ohms, and inductance 1 henry. The effective flux in the gap cannot be increased indefinitely, because leakage increases at a much greater rate than the effective flux and the magnet becomes uneconomic; nor can the gap be reduced, because the stiffness of the damping blocks must be increased to resist the static magnetic pull which will result in a higher playing weight and increased value of the low-frequency resonance.

In order to avoid second-harmonic distortion, the gap length must usually be considerably greater than the maximum deflection of the armature under operating conditions, and high permeability materials cannot usually be used because of danger of saturation.

A development of this type of pickup is shown in Fig. 8 in which the armature is suspended at the remote end. This is usually used with permanent styli, and the effective armature mass is reduced considerably compared to the earlier type. It is possible to reduce the effective mass to below 5 mg and to increase the compliance to about 2×10^{-6} cm/dyne. This results in good tracing capabilities, but the price paid is a very low over-all efficiency. The equation for the generating voltage is exactly the same as for the earlier unit, and apart from mechanical differences, the design of the two units is identical. Both pickups suffer from the dis-

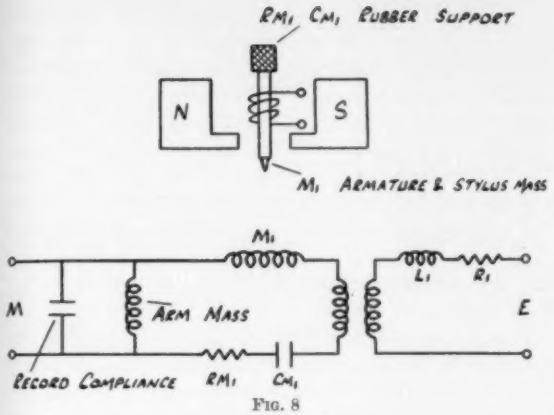

FIG. 8

advantage of inherently low vertical compliance, with the result that needle talk is excessive.

The first practical solution to wide-range reproduction with low mechanical impedance was achieved by Mr. Voigt with his long narrow moving coil, and the majority of moving coil pickups designed and manufactured today are based on the precepts laid down by this pioneer of high fidelity. Figure 9 shows a typical example. The coil is one of a light-weight plastic former, cylindrical in shape, has rubber tube bearings, and is supported in a uniform magnetic field. Rotation of the former results in voltage generated which is proportional to the field, the number of turns, and the velocity. It is possible to reduce the effective mass to about 5 to 7 mg for normal construction, and in the case of ribbon-type units to about half this value. The efficiency of both units is low, and unless precautions are taken in the case of the ribbon unit to have a completely balanced electrical system, the induced hum, especially in the connecting leads, can be serious. Because the coil and former are essentially non-magnetic, there is no tendency for the armature to stick to either of the pole pieces, and the bearings which are also

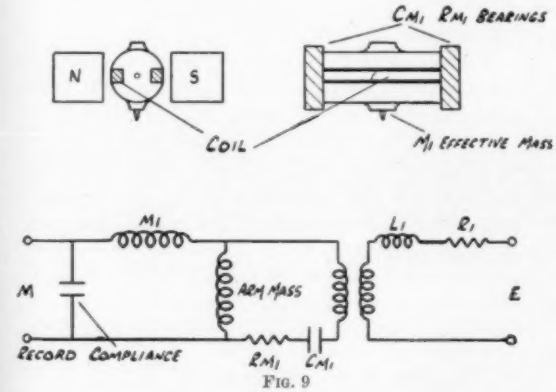

FIG. 9

used as restoring means can be made highly compliant. There is a limit, however; if they are made too compliant the armature will be deflected off center by the playing weight and will tend to roll on the top of the bearing. The plinth on top of the armature is used as a dynamic balancing medium; otherwise at high frequencies the center of gravity of the armature will move progressively from the geometrical center, resulting in the effective mass of the armature increasing with frequency. Attempts have been made in the past to minimize this by running the armature in needle-type bearings but the advantages are usually outweighed by the very serious mechanical difficulty of making a lighter bearing with a minimum of friction and no slop.

Taking present-day reproducers, the best moving coil units probably represent the epitome of high-fidelity design, with the exception of needle talk which is high, because the

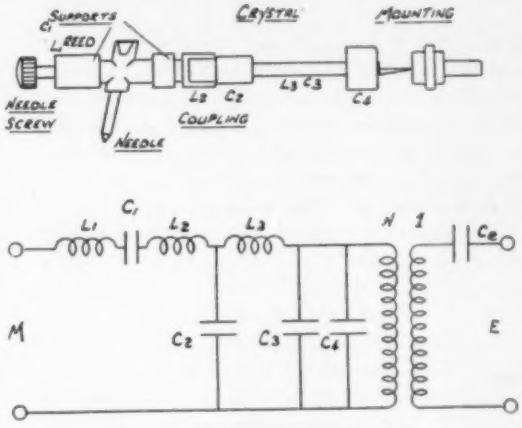

FIG. 10

relatively large area of the armature is rigidly connected to the stylus tip and is a very efficient radiator of sound energy at high frequencies. A recent continental pickup has been produced using a vertical coil with a cantilever-type stylus connected to it. This results in a very considerable reduction in needle talk without any loss of the advantages of the moving coil system.

Where high output is of paramount importance, as for instance in domestic receivers, the crystal pickup is pre-eminent over all other types. The electromechanical efficiency of rochelle salt is of the order of 60 to 70%, and this results in a total efficiency factor for high-impedance circuits about 10 times as great as for magnetic pickups with the same effective mechanical impedance. Figure 10 shows the schematic of a crystal pickup which has been the basic design for many years but at last is falling into disuse because of the changeover from steel needles to sapphire tips. The compliance was usually about 5×10^{-7} cm/dyne, and

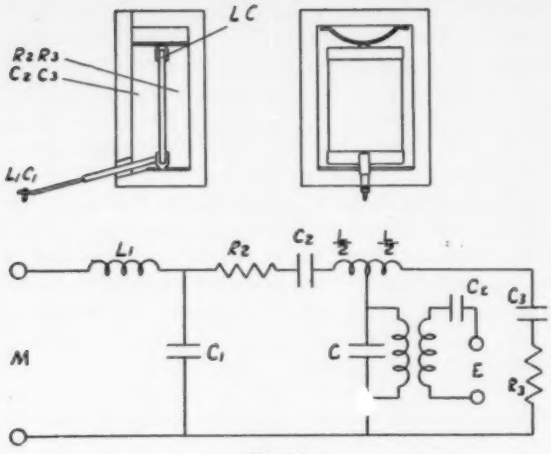

FIG. 11

the effective mass about 70 mg, requiring a minimum playing weight of about 1½ to 2 oz, with a low-frequency resonance of about 70 cps and a high-frequency resonance of between 4 and 7 kc, according to the type of needle used. The output voltage is quite fantastic, 10 to 12 volts being common on the more heavily modulated records. Therefore, like its old friend the balanced armature magnetic, it should now be considered a museum piece rather than a unit for serious consideration.

Finally there is the cantilever-type crystal unit shown in Fig. 11. The crystal is very freely suspended so that there is appreciable motion along its length. It is restrained at the remote end by material which has a high compliance but a very small resistance, and the cavity is filled with a highly viscous gel. By this means the correct ratio of resistance to reactance can be achieved easily in production. It has the added advantage that the crystal is hermetically sealed against moisture and that the damping is applied over the whole crystal rather than to one place only. The compliance is of the order of 3.5 to 5×10^{-6}, resulting in a low-frequency resonance of about 15 cps with a normal tone arm. The effective mass in the high-frequency region is about 5 mg, resulting in the resonance being about 17 kc, but because of the high damping factor applied it is more nearly correct to say that the system is aperiodic.

In the foregoing examples the equivalent circuit has been shown in a simplified version in that it only deals with the lateral components. As we have indicated, there is additionally a vertical component which in certain circumstances can affect the response of the pickup, and there is also a torsional component. The vertical compliance will resonate with the effective vertical mass of the tone arm in an exactly analogous manner to the lateral condition, and with some spring-loaded tone arms a highly efficient oscillatory circuit results, sometimes with Q's as high as 25. If this should occur either near the rumble frequency or in the lower recording range, trouble can be expected due to either increased motor rumble or groove jumping on heavily modulated passages, even though the cartridge itself is beyond suspicion. In the case of the torsional compliance the torsional moment of inertia of the arm is usually quite low and results in wiggles in the response somewhere between 200 and 600 cps. For these reasons the writer prefers a single point suspension with a counterbalance weight in order that the vertical resonance and the torsional resonance can be brought below the lateral resonance of the system.

It only remains now to stick the pickup head onto an arm and hope for the best. As is well known, if a straight arm is used a considerable tracking error can exist. This has been investigated by Bauer,[2] and he has shown that the distortion introduced by the tracking error is proportional to

$$K\frac{a}{r}$$

where K = constant.
a = tracking error.
r = radius of groove.

From this it will be seen that the distortion is proportional to the ratio between the tracking error and the groove radius; in other words, we can tolerate a greater degree of tracking error on the outside of the record than on the inside. For minimum distortion the overhang, D, of the head should be

$$D = \frac{r_1^2}{L\left[\frac{1}{4}\left(1+\frac{r_1}{r_2}\right)^2+\frac{r_1}{r_2}\right]}$$

and the offset angle, B, should be

$$B = \frac{r_1\left(1+\frac{r_1}{r_2}\right)}{L\left[\frac{1}{4}\left(1+\frac{r_1}{r_2}\right)^2+\frac{r_1}{r_2}\right]}$$

where L = tone arm length.
r_1 = inside radius.
r_2 = outside radius.

A tentative international standard has been promulgated for pickup arms in domestic reproducers with centers of 7 in. from pickup arm pedestal to turntable center, 0.6-in. overhang, and an offset angle of 26°. Using these values the maximum error occurs on the outside of the disk and is less than 3°, resulting in a maximum distortion due to this cause of approximately 0.2%.

That brings us to the end of fundamentals, and there is not much more to do now except to go home, assemble a few bits and pieces, and then listen to perfect reproduction.

[2] Bauer, *Electronics*, 18, 110 (March, 1945).

Etched Circuits for Audio

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Etched circuitry has advantages for both large-volume and small-volume production and for runs as short as twenty-five units. Current design practices are described, and data are presented for use in electrical and mechanical design of etched circuits. Production practices including dip-soldering are briefly outlined. New standard etched circuit boards for development-laboratory use are described: a series of six standard patterns provides basic circuitry for more than seventy-two commonly used tube types. Since no components are provided with these standard boards, the designer is free to select optimum values for his circuit conditions.

PRINTED CIRCUITRY has come into prominence in the last several years because it offers economy in production, simplifies servicing, and offers a number of other advantages to the producer and user of electronic equipment. The extent of interest is indicated by the volume of publication currently appearing in the technical press[1-8] and by the number of questions that are asked by engineers who are beginning to consider designing for etched circuit production.

It is possible to obtain some of the advantages of etched circuit design with only slight changes from conventional layouts. Ordinary turret-lug terminal boards, for example, may be designed with etched connections replacing hand-wired jumpovers. In few cases, however, can such a change be justified in dollars and cents. With more radical redesign, as by installation of tube sockets, capacitors, resistors, and the like on an etched board with their leads extending through the board so that all may be dip-soldered in a single operation, etched circuit economies become striking, even in short production runs.

Savings are obtained with etched circuits in several ways. First is the direct saving of production time in assembly and soldering. This may amount to half or more of the usual assembly time. Other savings accrue in the virtual elimination of wiring errors with consequent saving of check-out time, reduction of rework losses, and lessened inspection load.

A still further advantage appears in repair and maintenance. Components are readily accessible and may be fully identified by markings on the etched board. Components are easily replaced, since there is only one component lead connected at any point in the etched circuit, rather than several wrapped around a single lug as in conventional wiring.

These savings, important as they are in volume production, are usually minor compared to the saving in learning-time for short-run work. An inexperienced girl, working from a model, can reach a highly satisfactory production rate within a few hours' time when assembling parts to an etched chassis, with errors reduced to a vanishing minimum. For a typical five-tube plug-in computer subassembly, it has been calculated that production runs of twenty-five pieces or more can be produced more cheaply by etched circuit techniques than by conventional wiring.

ETCHED CIRCUIT DESIGN PRACTICE

Selection of Material

The designer has a wide variety of materials from which to choose. For highest service temperatures, under the most severe conditions, he may select Teflon-glass-cloth laminated board. For lower-cost high-temperature service, glass-silicone board may be used. Glass-melamine is often selected where arc resistance is important, and it will withstand temperatures somewhat higher than can be tolerated with phe-

[1] A. W. Kelly, "Review of New Printed Circuit Development and Audio-Frequency Applications," *J. Audio Eng. Soc.*, **1**, 53 (1953).

[2] J. Kanarek, "Application of Printed Circuits and Miniaturized Assemblies to Audio Amplifiers and Equipment," *J. Audio Eng. Soc.*, **1**, 202 (1953).

[3] Stones, "Printed Multiple Soldering Methods," *Tele-Tech*, **12**, 62 (December, 1953).

[4] Steigerwalt, "Embossed Wiring for Printed Circuits," *Tele-Tech*, **12**, 70 (December, 1953).

[5] Swiggett and Carberry, "Economics of Printed Wiring," *Tele-Tech*, **12**, 78 (December, 1953).

[6] Swiggett and Carberry, Directory, *Tele-Tech*, **12**, 88 (December. 1953).

[7] Weinberg and Martin, "Protective Coatings for Etched Circuits," *Tele-Tech*, **12**, 88 (December, 1953).

[8] W. Hannahs, J. Caffiauz, and N. Stein, "Standardization of Printed Circuit Materials," *Tele-Tech*, **13**, 68 (February, 1954).

TABLE I. Maximum Service Temperatures, Copper-Laminated Boards.

XXXP phenolic	120°C
Glass-melamine	135°C
Glass-epoxy	175°C
Glass-silicone	200°C
Glass-Teflon	200°C

nolic board. For lowest cost, phenolic boards of various grades may be used. Table I shows the temperature limitations of the common board materials.

For routine service where cost is a decisive factor, the usual choice is phenolic board from 1/32 to 1/8 in. thick—frequently 1/16 in.—depending on the area and mechanical stiffness required, with 0.00135-in. (1 oz) copper on one or both surfaces. There is considerable cost advantage in using single-surface board. A few drop-in wire jumpovers, judiciously located, will often save the cost of etching an entire side. Standard board material thicknesses are 1/32 to 1/8 in. by 1/32-in. increments. Standard copper thicknesses are 0.0007, 0.0014, 0.0028, 0.0040, and 0.0094 in.

Electrical Design

Current-carrying capacity of etched circuits is limited by the allowable maximum service temperature. The limiting temperatures indicated in Table I should not be exceeded in the conductors on the face of the board. However the high ratio of heat-dissipating surface to heat-generating cross-sectional area in etched circuit conductors allows comparatively heavy currents to be carried without undue temperature rise. Current ratings therefore are much higher than might be expected from the circular-mil area of the conductor. Table II gives maximum ratings in amperes for room temperature ambients. In practical design a safety factor of 2 or more should be used with these maximum ratings.

TABLE II. Maximum Current Ratings, Amperes.

Copper thickness, in.	Line width, in.		
	1/64	1/16	1/4
0.0014	3	10	23
0.0028	5	15	35

Note: Ultimate ratings given, based on 120°C board temperature and 25°C ambient. Use appropriate safety factor in design.

Electrical resistance of etched conductors is ordinarily considerably less than 0.5 ohm for any given conductor on a reasonably sized board. It may be estimated in the conventional way.

Arc-over voltages are equivalent to the arc-over voltage of the insulating board without etched circuitry. Good design for mechanical separation of conductors—1/32 in. or more—will ordinarily be satisfactory for peak voltages up to at least 1000 volts.

Capacitance between adjacent conductors is roughly equivalent to that found in conventional wiring. On phenolic materials 1/32-in. conductors, spaced 1/32 in., will show about 1.0 mmf per inch of parallel length. On melamine the capacitance will be slightly higher. This capacitance may be minimized by the usual precautions of keeping leads short and well spaced. For critical runs a ground strip may be run between the conductors in question. A major advantage of etched circuit design is that interconductor capacitance is sensibly constant from one assembly to another. The problem of variations due to minor differences in lead dress does not appear with etched circuits.

Coils up to about 20 μh inductance can be produced as part of an etched circuit board. Their design and use is a matter of cut-and-try after the number of turns has been estimated by standard air-core coil formulae.

Mechanical Design

Over-all costs may be minimized by using the etched board as a mounting plate for as many components as possible, eliminating the conventional metal chassis. This usually requires some thought and experimenting with unconventional layouts but is well worth while from a production-cost standpoint. All etching should be kept on one side of the board, and all components on the other. In some cases this can be done by using two spaced parallel boards, with components mounted between them and running from one to the other. Where it is not possible to arrange components in this way, marked savings can still often be obtained by using a combination of dip-soldering and hand-soldering techniques.

Minimum cost of circuit etching is obtained with generous conductor widths—1/16 in. or more—and generous spacing—1/16 in. or more. With these spacings and widths, inexpensive techniques can be used in production, and if all "drop-outs" are eliminated (such as occur in the letter "O" for example), still further production economies are possible in runs of several thousand or more pieces.

The minimum practical line width and spacing are each about 0.010 in. These spacings can be held if necessary for special reasons, but they should be avoided if possible, because of higher cost and a tendency for solder to bridge-over.

A 1/32-in. minimum radius of copper should be allowed all around holes, lugs, eyelets, and the like to allow solder buildup and to ensure good joints.

Large solid copper-covered areas should be avoided. Difference in expansion between copper and board tends to cause warping in service. The copper should be broken up into a series of separate conductors.

For high production and minimum expense, a simple No.

45 drill-size hole serves to mount resistors and capacitors by their leads. Where hand-soldering is done, or where there will be considerable changing of components and servicing, eyelets should be set in each component mounting hole. Larger lugs may also be used, but because of their mass they heat up more slowly during dip-soldering and take longer to cool, causing some hazard of local overheating of the board material. It is essential that all joints be thoroughly soldered, including the joint between eyelet or lug and the copper strip.

Bare copper oxidizes rather quickly, making soldering difficult. For this reason, it is customary to specify a coating over the etched conductors. Least expensive is a fluxing varnish that also serves to insulate and protect the board material from moisture during service. This material cures when dipped in the solder pot and remains on the board during its service life. Other finishes are hot-tinning, electro-tinning, silver-plating, nickel-plating, rhodium-plating (usually over nickel) for hard-wearing contacts, and gold-plating.

Other uses for circuit etching include production of switch assemblies, with copper flush with the board surface, wave guides, and boards with lettering as a replacement for expensive machine-engraving.

Components

Components especially designed for use with etched circuits are being produced by a number of manufacturers, and more are continually being introduced. Table III lists a number of sources of components for use with etched circuits. It should be regarded as a partial guide, not as a complete directory.

TABLE III. Sources of Etched Circuit Components.

Potentiometers

Chicago Telephone Supply Corp.
Elkhart, Ind.

Centralab
934 E. Keefe Ave.
Milwaukee, Wis.

Tube Sockets

Methode Mfg. Corp.
2021 W. Churchill St.
Chicago 47, Ill.

Eby, Inc., Hugh H.
4700 Stenton Ave.
Philadelphia 44, Pa.

Elco Corp.
190 W. Glenwood Ave.
Philadelphia 40, Pa.

Connectors

DeJur Amsco
4501 Northern Blvd.
Long Island City, N. Y.

Johnson Co., E. F. (Viking)
242 Second Ave. S. W.
Waseca, Minn.

Winchester Electronics, Inc.
15 Crescent Rd.
Glenbrook, Conn.

Circon Component Co.
17544 Raymer St.
Northridge, Calif.

Capacitors

Mallory & Co., Inc.
3029 E. Washington St.
Indianapolis 6, Ind.

Relays

Allied Control Corp.
2 East End Ave.
New York 21, N. Y.

Transformers

Microtran Co.
2117 Mott Ave.
Far Rockaway, N. Y.

Coils

Automatic Mfg. Corp.
65 Gouverneur St.
Newark 4, N. J.

Resistors-Integral

Dwyer Engineering Co., Inc.
P. O. Box 483
Nashua, N. H.

Rectifiers, Selenium, Power Supply

Federal Telephone & Radio Co.
100 Kingsland Road
Clifton, N. J.

ETCHED CIRCUITS IN PRODUCTION

The principles of dip-soldering are the same as those of any soldering operation. Joints must be mechanically solid, surfaces must be clean and well fluxed, and all parts of the joint must reach soldering temperature.

Two additional points must also be watched in dip-soldering. First, the time during which the board is exposed to solder temperatures must be held to a minimum, and second, provision must be made for "cleaning-up" the solder and eliminating possible bridging.

Cleanliness is assured by specifying that the etched circuit be coated by the etcher with a protective flux varnish after his thorough clean-up. This also accomplishes the necessary fluxing. Solder is selected for minimum melting temperature and greatest fluidity. Sixty per cent tin or eutectic composition is often used. The temperature of the solder bath is carefully controlled. Parts of the assembly that are to be kept free of solder are masked with self-adhesive tape or labels or, for high production, by a masking fixture that holds the assembly while it is dipped in the pot. Length of time in the solder bath must be determined by trial, and will be of the order of 5 seconds in solder at 400° to 425°F. Then a second dip in baker's pan oil or high-temperature wax at about the same temperature smooths the solder and eliminates bridging. Production-line equipment for dip-soldering consists of one or two temperature-controlled pots, any necessary flux containers, and racks and jigs for holding assemblies. For preliminary experimenting, solder may be melted in a simple cast-iron skillet on a gas hot plate and its temperature measured with a laboratory-type high-range glass thermometer.

Changing over from hand-wired to etched circuit production is very inexpensive. Since first-piece cost for etched boards is ordinarily of the order of $50.00 or less, etched circuitry savings are now available even to the smallest production plants.

ETCHED CIRCUITS IN DEVELOPMENT WORK

Etched circuits have not heretofore been used in development work because no suitable standard circuits have been available. Upon consideration of the circuitry associated with the typical tube types in common use, however, it

TABLE IV. Tube List.

Tube No.	Name	Tri-Dex Part No.
6A5G*	Octal pentode	Q-289-1
6AB7	Octal pentode	Q-288-1
6AC5GT*	Octal pentode	Q-289-1
6AC7	Octal pentode	Q-288-1
6AG5	Minipentode	Q-301-1
6AG7	Octal pentode	Q-288-1
6AH6	7-pin minipentode	Q-301-1
6AK5	7-pin minipentode	Q-301-1
6AQ5	7-pin minipentode	Q-301-1
6AR5	7-pin minipentode	Q-301-1
6AS7G	Octal duo-triode	Q-298-1
6AU6	7-pin minipentode	Q-301-1
6B4G*	Octal pentode	Q-289-1
6BA6	7-pin minipentode	Q-301-1
6BC5	7-pin minipentode	Q-301-1
6BD6	7-pin minipentode	Q-301-1
6BF5	7-pin minipentode	Q-301-1
6BH6	7-pin minipentode	Q-301-1
6BJ6	7-pin minipentode	Q-301-1
6BQ6GT	Octal pentode	Q-289-1
6C5*	Octal pentode	Q-289-1
6C5GT*	Octal pentode	Q-289-1
6F6	Octal pentode	Q-289-1
6F6G	Octal pentode	Q-289-1
6F6GT	Octal pentode	Q-289-1
6G6G	Octal pentode	Q-289-1
6J5*	Octal pentode	Q-289-1
6J5GT	Octal pentode	Q-289-1
6K6GT	Octal pentode	Q-289-1
6K7	Octal pentode	Q-289-1
6L5G*	Octal pentode	Q-289-1
6L6	Octal pentode	Q-289-1
6L6G	Octal pentode	Q-289-1
6N7	Octal duo-triode	Q-297-1
6N7GT	Octal duo-triode	Q-297-1
6S7	Octal pentode	Q-289-1
6S7G	Octal pentode	Q-289-1
6SC7	Octal duo-triode	Q-298-1
6SG7	Octal pentode	Q-288-1
6SH7	Octal pentode	Q-288-1
6SH7GT	Octal pentode	Q-288-1
6SJ7	Octal pentode	Q-288-1
6SJ7GT	Octal pentode	Q-288-1
6SK7	Octal pentode	Q-288-1
6SK7GT	Octal pentode	Q-288-1
6SL7GT	Octal duo-triode	Q-298-1
6SN7GT	Octal duo-triode	Q-298-1
6SN7GTA	Octal duo-triode	Q-298-1
6SS7	Octal pentode	Q-288-1
6U6GT	Octal pentode	Q-289-1
6U7G	Octal pentode	Q-289-1
6V6	Octal pentode	Q-289-1
6W6GT	Octal pentode	Q-289-1
6W7G	Octal pentode	Q-289-1
6Y6G	Octal pentode	Q-289-1
6Z7G	Octal duo-triode	Q-297-1
and the 12-v equivalents of the above tubes		
12AT7	9-pin mini-duo-triode	Q-302-1
12AU7	9-pin mini-duo-triode	Q-302-1
12AX7	9-pin mini-duo-triode	Q-302-1
12AY7	9-pin mini-duo-triode	Q-302-1
12BH7	9-pin mini-duo-triode	Q-302-1
1223	Octal pentode	Q-289-1
1631	Octal pentode	Q-289-1
1632	Octal pentode	Q-289-1
1633	Octal duo-triode	Q-298-1
1634	Octal duo-triode	Q-298-1
1635	Octal duo-triode	Q-297-1
1852	Octal pentode	Q-288-1
1853	Octal pentode	Q-288-1
5691	Octal duo-triode	Q-298-1
5692	Octal duo-triode	Q-298-1
5881	Octal pentode	Q-289-1
7000	Octal pentode	Q-289-1
KT-66	Octal pentode	Q-289-1

* Triodes, using pentode boards.

appears that certain basic circuits are repeatedly used in constructing a wide variety of equipment. Two of the most common of these circuits are the simple resistance-coupled triode and resistance-coupled pentode amplifier circuits. Nearly all vacuum-tube circuits in common use today may be regarded as variations of these two basic circuits. It appears possible, then, that some standardization of circuitry may be possible in terms of these basic building blocks.

Some attempts along these lines have been made in the past, and standard interstage coupling circuits are now commercially available, containing both wiring and components. Since these circuits already contain fixed resistors and capacitors, however, they tend to limit the designer's choice of circuit conditions. Either a large number of different circuit units must be at hand, or a severe limitation is placed on the number of tubes and on the circuit parameters that the designer may select.

By omitting the components and supplying only the prefabricated wiring, it has recently been found possible to provide the wiring for a large number of commonly used tubes, in their basic circuits, in the form of a series of only six compact etched circuit boards.

Tubes and circuits include octal triodes, octal duo-triodes, octal pentodes, miniature pentodes, and miniature duo-triodes. A partial list of tube types for which these standard etched circuits may be used is given in Table IV. Since no components are included with the standard boards, the designer is free to choose the best resistor and capacitor values for his own unique selection of tubes and operating conditions. Figures 1 and 2 show a typical circuit pattern of this series of boards, as well as that of a universal prefabricated power-supply circuit.

These standard etched circuits, known by the trade name of Tri-Dexes, are installed in the chassis by mounting directly on the conventional tube sockets. Extra-long screws are used to mount the tube sockets in the usual way. Extra

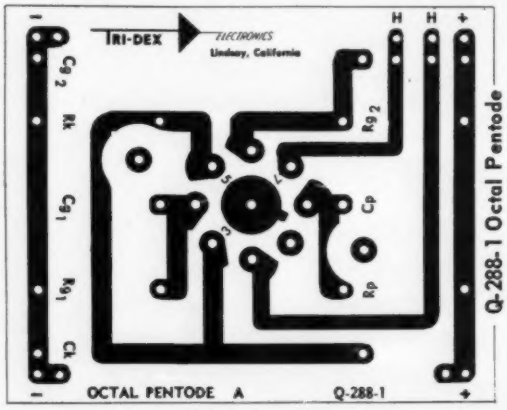

FIG. 1. Pentode.

nuts are then run on the screws, and the standard boards are placed in position so that the tube socket tabs project through the board. The tabs are bent over, and the board is brought back up into firm contact with them and is held there with the extra nuts underneath. Additional nuts are then run on to lock the board firmly in place, and the tabs are soldered to the etched conductors. The components are then mounted and soldered in their eyelets.

Component locations are marked according to conventional notation, R_k indicating cathode resistor, C_{g2} indicating screen grid bypass capacitor, and so on. All resistor eyelets are located on ¾-in. centers and all capacitor eyelets on 2-in. centers so that component leads may be precut and preformed for rapid mounting. These spacings allow use of the largest resistors and capacitors commonly employed in audio circuits, and it has been found that the compact arrangement possible with circuit etching allows all components, even for an octal duo-triode, to be mounted on a 2½ by 3-in. board. Component leads are soldered into their eyelets in the usual way. Ground, B+, and heater connections are brought to marked eyelets at the edge of each board, and interstage coupling is accomplished by using the coupling capacitors as stage-to-stage jumpers.

A flat aluminum shielding plate is provided with each standard etched circuit. These plates mount on the same long screws, spaced above the mounted components with extra nuts, and serve to shield each stage separately for high-gain audio work. Standard shield cans may be used in the same way if necessary for stage-wise shielding.

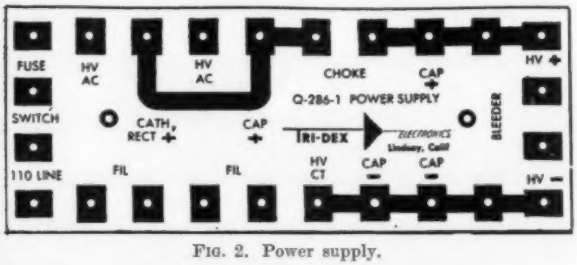

FIG. 2. Power supply.

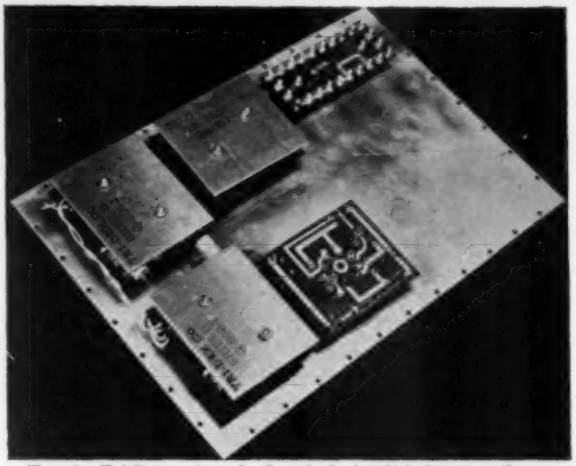

FIG. 3. Tri-Dexes (standard etched circuits) in a partly completed experimental Williamson-type amplifier.

By using the standard boards themselves as marking templates, chassis layout time is reduced. Assembly of parts is made quick, simple, and nearly foolproof. The resulting circuit is neat, strong, easy to follow and check, and exceptionally easy to service. Wiring errors are practically eliminated, and checkout time on a new circuit is reduced to its barest minimum. Because of the economies thus made possible, these standard etched circuits are of particular value to development laboratories and engineers engaged in design of advanced audio equipment, as well as to engineers who have only occasional need to build up special equipment for studio or laboratory purposes.

Fig. 3 shows Tri-Dex standard etched circuit boards in a partially completed developmental Williamson-type amplifier.

The Mechanics of Good Loudspeaker Design

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ALTHOUGH a loudspeaker is invariably associated with electronic equipment, the degree to which it performs acoustically is strictly a matter of mechanics. Those characteristics of a loudspeaker which are a measure of the quality of its reproduction, such as frequency response, polar distribution, acoustic power-handling capacity, and cleanliness of response, may all be resolved through the general theory of mechanical structures in terms of physical stresses and strains. Once the magnitude of these stresses and strains is realized, one may begin to appreciate the severity of the task imposed on the loudspeaker in satisfying the critical ear.

The mechanical stresses that a good loudspeaker is required to withstand are in some respects greater than those stresses which our giant supersonic aircraft meet. The sound-producing element of the loudspeaker, the vibrating paper cone, or diaphragm, undergoes far greater values of acceleration than the fastest of airborne equipment. Unclassified government sources come up with a figure of approximately 10*g* as being the highest acceleration yet attained in an aircraft coming out of a dive. One *g* corresponds to a force equal to the weight of the object. In contrast, that little piece of vibrating paper, commonly referred to as the cone of the loudspeaker, may be subjected to an acceleration close to 10 times 10 in coming out of its "dive" at the end of every vibrational cycle.

Figure 1 illustrates the simple conical diaphragm of a 12-in. speaker. If the motion is sinusoidal, the maximum acceleration is given by

$$A = \frac{4\pi^2 S}{T^2}$$

where S is the maximum displacement from the rest position, and T is the period. For the speaker to radiate 1 acoustic watt at 60 cps, the value of S must be about ¼ in.; the period T is 1/60 second. This gives for the maximum acceleration the value 2960 ft/sec/sec, equivalent to 93*g*. Assuming this speaker to be of the wide-range family capable of operating out to 10,000 cps, we may then make another

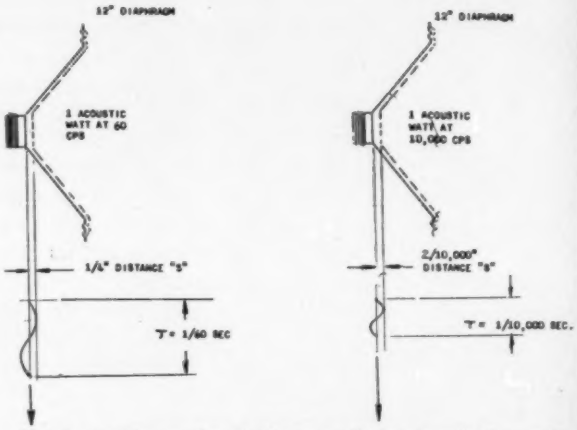

FIG. 1. A 12-in. speaker diaphragm radiating 1 watt of acoustic power.

quick calculation for the acceleration of the vibrating diaphragm when 1 acoustic watt is radiated at this frequency, assuming the whole diaphragm to vibrate in phase. The peak excursion of the diaphragm in this instance will be 2/10,000 in. Pushing these figures through the slide rule brings forth the figure of 2060*g*.

If we bear in mind that a typical paper diaphragm which undergoes these values of acceleration may be but a few ten-thousandths of an inch thick, it is amazing that it doesn't literally "black out" and fall apart the minute it begins to play. Well, loudspeakers actually do black out, and the degree to which they black out will determine whether the loudspeaker, while undergoing these stresses, will be nothing more than just strained a bit while buffeting the dive (Fig. 2) or veritably disintegrate in the process. Whether it does one or the other will be determined by the mechanical design of the instrument and the precision with which it was made.

This discussion of the mechanics of loudspeaker design was started with the diaphragm for two reasons: first, to illustrate the unusual stresses to which one component of

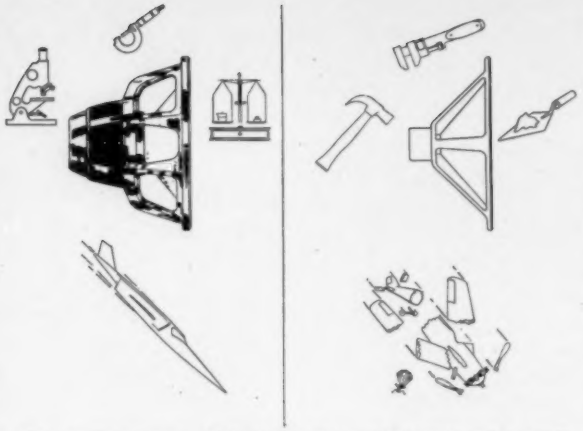

FIG. 2. To overcome high-acceleration "blackout" and acoustic disintegration, loudspeakers must be precision-built for optimum mechanical strength.

the loudspeaker is subjected, and the relative frailty of that component in which the resultant strains are produced; second, because it is the all-important diaphragm alone which produces the sounds we hear. The shape, size, weight, and contour of the diaphragm are somewhat more than a matter of artistic taste. Scores of patents held by the manufacturers of loudspeaker diaphragms attest to the fact that the science of paper pulp manufacture and the physical characteristics of paper geometrical forms mean as much to loudspeaker performance as do blocked impedance, flux density, power input, and similar terms. The actual ingredients that go into the making of any particular diaphragm are probably as much of a trade secret to the manufacturer of the diaphragm as are the ingredients of any patented drink concoction.

The trade secrets in bottles may well take the enamel off our teeth, after the first flush of flavor has passed away, but the trade secrets compounded into a loudspeaker diaphragm are intended to bring lasting pleasure to the listener. So we will forgive the vendor of diaphragms his desire for secrecy. However, the loudspeaker manufacturers cannot let these trade secrets go entirely unchecked. The compounding of a diaphragm for a particular acoustic response is just as critical for the loudspeaker as is the compounding of a vitamin product for a particular physiological response. Careful acoustic checks on the end of a loudspeaker production line may show up a change of ingredients at the pulp-mixing vats of the diaphragm manufacturer's plants.

The writer was made painfully aware of this circumstance when inspection reports coming to his desk showed a sudden deterioration in the high-frequency response of a particular model running through production. Production was immediately stopped for trouble shooting. The culprit was eventually identified as the diaphragm itself. Even though pre-production checks of these diaphragms showed them to fall within design specifications of weight, thickness, resonance frequency, and dimensional tolerances, yet their acoustic response had somehow suffered. On checking with the vendor of the diaphragm, we were informed that the pulp formulation from which the diaphragm was molded had a temporary domestic ingredient substituted for a Swedish pulp ingredient which was on the hard-to-get list at the time. Although such temporary substitution of an ingredient in the paper pulp did not affect the run-of-the-mill "wide-range" diaphragm, it did show an effect where that last little "tingle" was expected from a particular diaphragm. Needless to say, the vendor was happy to correct the pulp formulation, and we were even happier to start up production again.

Paper stock is all-important to loudspeaker performance. Figure 3 gives a graphic acoustic comparison between two diaphragms of the same resonance, same weight, same thickness, but of different paper stock, one classified by the vendor as a "hard" stock, the other as a "soft" stock. The design problem involved here was to select a diaphragm for a 12-in. concentric coaxial loudspeaker. Now, although it is well recognized that in a true two-way loudspeaker system there should be a definite division of acoustic response between the woofer and the tweeter, the means of attaining such division may be electrical or mechanical. Such frequency division may be accomplished electrically by adequate crossover networks, or mechanically by selecting diaphragms that lose radiating efficiency in the band in which they are not to be effective, or by a combination of both. Thus, from an inspection of the curves in Fig. 3, it might appear that the diaphragm to be selected for the woofer portion of the loudspeaker would be the one marked soft stock, since this rolls off in efficiency for the high frequencies start-

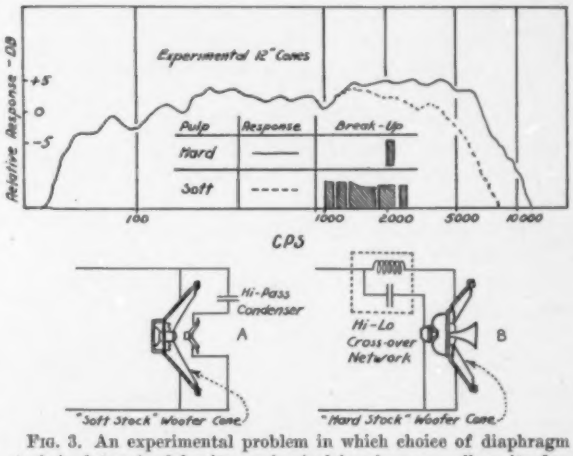

FIG. 3. An experimental problem in which choice of diaphragm stock is determined by its mechanical breakup as well as its frequency response.

ing at 2 kc. Such an acoustic frequency rolloff would simplify the electrical crossover network. In such instances it is common to find simply an isolating condenser as a crossover network between the woofer and the tweeter. In the case of the hard-stock diaphragm it would be necessary to include a network at the input to the two speakers whereby the inductive element of the crossover network would electrically block the high-frequency signals from getting into the woofer cone. The high-frequency radiation from the hard cone would consequently be reduced, by means of the electrical network, to the equivalent level of radiation of the high frequencies from the soft diaphragm without benefit of the choke.

At first glance, then, it would seem that the soft diaphragm would result in the more economical design. There is more to loudspeaker performance than range of frequency response, however. We must concern ourselves with the cleanliness of that response as well. Diaphragms have "breakup" characteristics. They play along very nicely as the applied frequency is increased until somewhere in the middle of their response they "cry" out at some frequency totally unrelated to the applied frequency. It is a harsh, unmusical sound which cannot be tolerated in good loudspeaker design. Like a supersonic plane trembling throughout its entirety when it reaches the sonic barrier and then settling down once it has broken through, so the loudspeaker diaphragm trembles wildly as it hits this breakup area and then settles down once it gets through. Like aircraft, those diaphragms which are mechanically stable will "cry" the least, and the unstable diaphragms will suffer the most when hitting this breakup barrier.

All the other mechanical factors being equal, the degree of breakup will be determined by the diaphragm pulp formulation. Thus we see that in Fig. 3 the breakup spectrum for the soft stock covers the entire octave from 1 to 2 kc, but the breakup characteristic for the hard stock occurs only in one small spiked area at 2 kc. Considering, then, the quality of the response desired, rather than the economics of obtaining it, the hard-stock diaphragm now seems to be preferred in this design problem, for in its operating range up to the 2-kc crossover point the hard-stock diaphragm will give clean reproduction whereas the soft-stock diaphragm will have considerable "cry" in its operating range.

It will be realized that choosing a type of diaphragm with some fair degree of high-frequency efficiency makes a choke necessary in the woofer circuit to reduce its high-frequency radiation in the band normally to be covered by the separate tweeter section. But this reduction of the high-frequency radiation is not accomplished by dissipative means, as is the case illustrated in Fig. 3, that of the soft stock. In this latter type of design, it is true that the soft cone may not radiate the high frequencies, but this is accomplished through (a) energy transmission losses through the soft texture of the cone itself and (b) the electrical loss of high-frequency signals in the voice coil. In contrast, the choke in the woofer circuit of *B* of Fig. 3 is an effective road block preventing the high-frequency signals from getting into the woofer voice coil. It shunts them into the tweeter unit instead, through which units they may be more efficiently reproduced. In the over-all picture, then, the design which used up the *electrical* energy most efficiently, and gave the optimum *acoustic* performance, was resolved on the basis of the *mechanical* structure of the diaphragm.

Before we leave the matter of diaphragm pulp formulation it will be of interest to examine another aspect of performance very much dependent on the pulp brewmaster's techniques. Paper, wool, and other fibrous ingredients that go into the manufacture of the diaphragm are all hygroscopic in nature. They will all absorb moisture to various degrees, depending on the nature of the particular ingredients used and the resins and waterproofing substances blended in with the pulp materials. Just as any ordinary absorbing material becomes limp when subjected to moisture, so also may a loudspeaker diaphragm become limp to a considerable degree. In consequence of such moisture absorption its mechanical stability and mechanical characteristics may be very much altered, and its acoustic response will suffer. Consider a loudspeaker that performs adequately in the normal atmospheric conditions prevalent over the major areas of this country. Now build this loudspeaker into a receiver to be operated in the hot humid lands in the equatorial or near equatorial belts. If the diaphragm has not been adequately treated with water-resistant ingredients, its performance under these tropical conditions will be entirely different from its performance in the manufacturer's laboratories. And when a manufacturer is called on to produce a quality item in quantity for export to such localities, he must perforce busy himself with humidity problems as they affect his product.

Figure 4 illustrates the performance of a garden variety

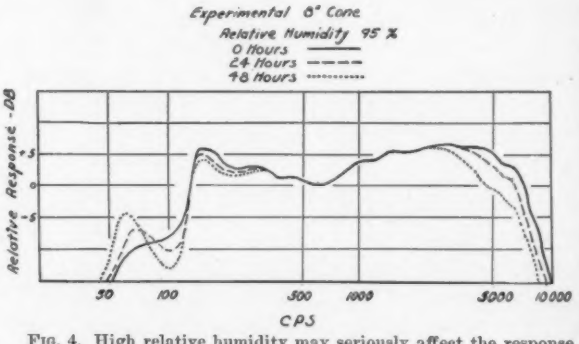

FIG. 4. High relative humidity may seriously affect the response of a hygroscopically unstable diaphragm.

type of 8-in. loudspeaker before and after being subjected to 24 and 48 hours of 95% relative humidity. It is apparent that, were this speaker to be tested in the customer's laboratory after sitting around on the test bench for a couple of days during a hot humid spell, it might very well fall below specified tolerances on the upper frequency limits. The reasons for this high-frequency loss under these conditions are twofold. First, the diaphragm, in absorbing moisture, has become heavier and in consequence vibrates to a lesser degree for a given applied electrical signal, which means less acoustic output. Second, in absorbing moisture the diaphragm has become relatively soggy and flabby and has lost its stiffness. In consequence of the added water weight, the decreased high-frequency transmission through the soggy paper of the cone, and the lowering of the resonance of the system, the high-frequency radiation suffers. Figure 4 shows the relative increase in low-frequency response due to this lowered resonance after 24- and 48-hour intervals.

In addition there are energy transmission losses through the soggy pulp material itself which reflect itself in more high-frequency losses. And yet this problem may not be entirely licked simply by waterproofing methods, for excessive treatment of this nature simply adds bulk and mass to the diaphragm which in turn are reflected in high-frequency loss. The more efficient attack is to select a diaphragm of which the ingredient fibers are least hygroscopic. But here we have a Gordian knot to cut. If we choose nonhygroscopic fibers, how then may we expect them to absorb enough of the binding fluids in the mixing vats to ultimately hold them together? A partial answer lies in selecting the proper length of these fibrous ingredients. If they are not cut too short, they will interweave one with another and form a stable paper compound. And there in the diaphragm mixing vats we have the core of much of our acoustic problem: soft or hard stock, long or short fibers, resins and waterproofing, all blended together to produce a given structure that will yield the desired *mechanical* characteristics that will in turn yield the proper *acoustic* response.

We have been using the term "diaphragm" instead of "cone" when referring to this vibrating element of the loudspeaker for very valid reasons, despite the fact that our subject concerns itself with the cone type of loudspeaker. Of course the word "cone" is not a misnomer. In the early days of the loudspeaker and in the days before the advent of the molded cone, it was easy to fabricate a paper form in three dimensions by the simple expedient of cutting a piece of flat paper to the desired shape, rolling it up, and then cementing the seam, thus producing a cone-shaped form. And so through long usage we refer to cone-type loudspeakers when very frequently the vibrating diaphragm is not cone-shaped at all. What we wish to stress at this point, however, is quite basic, and that is the very *need* to employ a generally

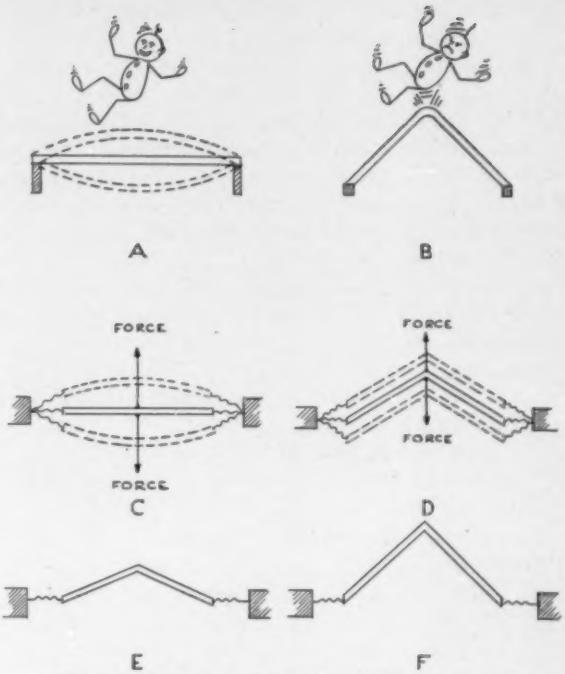

FIG. 5. The strength of a vibrating surface depends on its contour as well as on its thickness.

conical-shaped vibrating element in loudspeaker design. And the answer again returns us to the mechanical aspects of the strength of the structure.

Our very rigorous engineering and acoustic textbooks give us adequate mathematical means of determining any results we are looking for from "a plane piston" in a semi-infinite baffle. Then for practical illustration they proceed to calculate the performance of a *conical* vibrating surface. But we know that it is impossible to apply a vibrating force to the center of a flat surface and expect it to vibrate as a whole without any lateral flexing. Figure 5 illustrates certain basic truths concerning the strength of physical structures. In *A*, a vibrating impact will cause the flat piston to bow in and out under the impact, especially if the piston is thin in cross section, and large in area. In contrast, the conical shape, *B*, will resist all such efforts to make it flex. Thus we have arched bridges and vaulted domes; in their shape is their strength.

Accordingly, if we translate these basic principles of mechanics into loudspeaker application we will find that a relatively flat, shallow piston, free to move at its edges, will, under vibratory force applied to its center, bow itself in and out as it moves (*C*) and in so bowing will deteriorate its action as a rigid piston. In contrast, the conical-shaped diaphragm of *D* will maintain its rigidity relatively un-

changed as it moves back and forth under the vibrating impulse applied to its apex, and its piston-like action will remain relatively unaltered. The greater the excursion limits expected of this vibrating cone, due to greater applied vibratory force to its apex, the more rigid it should be. Such rigidity may be obtained by increasing the depth of the cone *(E–F)*. This reflects itself in a heavier structure, however, one of greater mass if the base diameter of the cone remains unchanged. More mass means lower resonance frequency; and other factors remaining unchanged, the high-frequency response is deteriorated. In consequence we find that such deep conical structures are admirably adapted for woofer application. We consequently make the cone deeper because we need the added strength of a deep cone to withstand the large low-frequency excursions expected of a good woofer. Without this structural strength of the cone, its piston action would be altered, and its low-frequency reproduction would suffer. Here again the acoustic performance of the loudspeaker in the range for which it was designed is very much dependent on the general theory of mechanical structures.

The fact that a deep cone becomes in essence somewhat of a horn projector need not cause us any concern in this application, for those low frequencies with which we are here concerned are large in wavelength compared to the dimensions of the piston and so are quite readily diffracted over an essentially hemispherical surface.

One of the most critical mechanical problems that the loudspeaker designer must solve is that of maintaining proper alignment of the voice coil as it vibrates back and forth in the magnetic gap. Any tendency of the voice coil to rock away at an angle from the central axis of vibration will result in a rubbing voice coil. Such rubbing will, of course, cause harshness of response, and what is more important it will eventually result in a ruptured coil. The commonly recognized means of maintaining voice coil concentricity within the gap is the centering spider. But the most unrecognized cause of eccentricity is the mechanical construction of the basket. The primary purpose of the basket is to support both the vibrating mechanism and the magnetic structure within which the voice coil vibrates. The second function of the basket is to provide some means of mounting the loudspeaker to its baffle board. Often the baffle against which the speaker is mounted may be slightly warped. In bolting down the speaker frame to a warped surface, the basket itself may be deformed unless it is mechanically rigid enough to withstand these unequal stresses created within the basket by forcing its contour to mate with an irregular baffle surface.

Such basket deformation will reflect itself in a change in the relative positions of the voice coil to the magnetic gap, both of which were originally aligned together in an

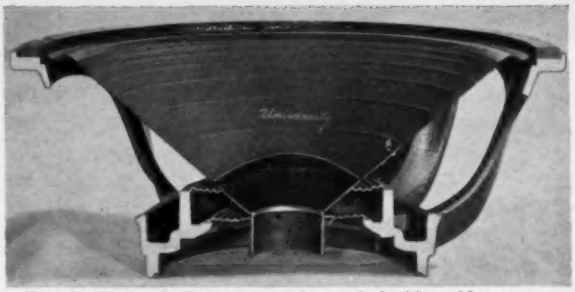

FIG. 6. Girder basket construction and double spider arrangement ensure minimum basket deformation and precision voice coil alignment.

undistorted basket support. Further deformation of the basket may be produced by the weight of magnetic circuit iron hanging out from the rear end of the basket. The heavier the magnet, and its associated iron circuit, the stronger must be the supporting basket. In modern loudspeakers designed for good low-frequency acoustic output, the trend is toward more and more pounds of magnets. And in turn more pounds of magnet call for stronger supporting structures. In general, it will be found that a basket stamped out of sheet metal stock is sturdy enough to support a moderate-size magnetic pot structure without undue deformation. If a design calls for extremely high acoustic output and high conversion efficiency for low-frequency radiation such as is expected from a good 15-in. speaker, however, then we will usually find that the combined weight of the magnet and its associated iron circuit will be of such magnitude that greater structural strength will be required of the basket than is possible from bent sheet metal. Moreover, the larger these baskets, the more easily the mounting edge may be twisted out of shape on irregular baffle surfaces. Because of the structural requirements of these large baskets for high power and high efficiency, one will usually find that the basket is die cast in a form that best embodies the basic principles of structural mechanics. Figure 6, a newcomer in the 15-in. woofer class, illustrates the "girder" type of mechanically rugged design that has to go into a loudspeaker basket to ensure optimum resistance to mechanical deformation of the basket during mounting and to maintain such mechanical stability over long periods of operation that will guarantee against damaging misalignment of the coil and the gap.

When one sees such massive structures in loudspeaker units, he can be sure that the psychological advantage of impressing the observer with its bulkiness was secondary in the manufacturer's mind to the need for employing the proper mechanics to achieve good loudspeaker design.

Having thus dealt briefly with one of the unrecognized causes of gap and voice coil misalignment, we must complete the study of the problem by considering the more commonly

recognized cause of such misalignment. Damaging eccentric and rocking motion of the voice coil about its axis of motion will occur while it is vibrating, if the means used to maintain accuracy of such motion are inadequate to meet the mechanical requirements imposed on the system by the large power output expected of it. The usual means for preventing such side swaying of the voice coil motion is the well-known spider located directly at the voice coil area. Examination of Fig. 6 will disclose that here is a new and exceedingly successful solution to the problem of maintaining precision voice coil alignment during vibration. Placement of two axially spaced spiders at the apex area of the vibrating system provides a dual guide to the vibrating system that keeps the voice coil motion rigidly channeled along one line of vibration that neither deviates in angular direction from the central axis nor becomes eccentrically located in respect to this axis.

Such maintenance of precision mechanical alignment pays off in more than just long life expectancy for the unit. It reflects itself in greater sound output as well, since this precision motion makes it possible to design the magnetic gap to closer tolerances than is normally the case. There is subsequently more gap flux realized, and greater acoustic conversion efficiency results. Here, again, the application of rigid mechanical theory leads to better loudspeaker performance.

Loudspeakers are not disembodied devices. They must be adequately baffled for optimum performance. Too often, however, the baffle had been considered simply as a convenient way of supporting and hiding the loudspeaker. Fortunately, those days are over, and the baffle is recognized as an integral component of the loudspeaker system, a component which in its own way contributes a great deal to the acoustic excellence of a speaker system. We simply have to take cognizance of the flurry of new loudspeaker enclosures that have hit the market within the last two years, each with its own newly perfected but still basic principles, to realize the truth of the above statement. However, whatever the so-called revolutionary development that any one of these baffles may claim as its own, they must all recognize that their mechanical construction is probably just as important in getting good acoustical results as is the theoretical acoustic basis on which they are designed. The quality of their mechanical construction is the basic common denominator of all baffles, especially those for low-frequency application. This being so, let us examine the simplest type of enclosure in present use today, the simple bass reflex cabinet. We will see to what extent its performance may be deteriorated by the nature of its mechanical construction, even though its internal volume, internal damping, and port area are acoustically and theoretically correct for the particular loudspeaker to be used with that cabinet.

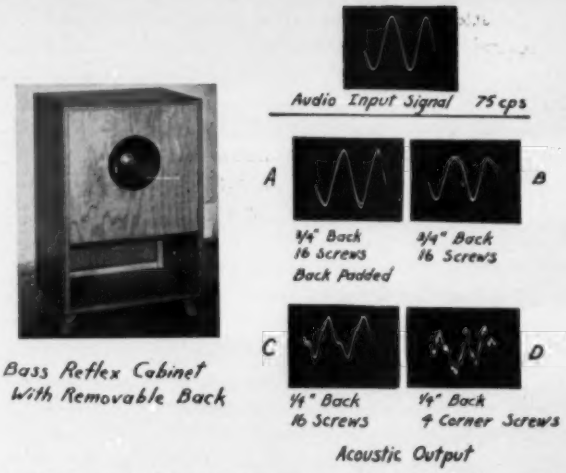

FIG. 7. Good baffle construction is reflected in good acoustic performance.

Figure 7 shows a typical bass reflex type of cabinet for housing an 8-in. speaker. This cabinet has a removable back for purposes of mounting the loudspeaker on the inside surface of front panel. This back panel, being out of sight, is too often out of mind. Especially does the home constructor fall into the pitfall of assuming that, because this back is removable, it is also almost expendable. He seems to forget the standard advice to make sure that all panels of the enclosure he is building be well glued and screwed together, that they be made of rigid panels at least ¾ in. thick, and that they be well braced. The back just doesn't seem to be part of the scheme of things, and more often than not he seems satisfied to secure the back panel by the four corners only. To illustrate the importance of the mechanics of enclosure construction on the quality of good acoustic results a series of tests were constructed on that cabinet. Two backs were constructed, one a ¼-in. plywood panel, and the second the recommended ¾-in. panel. A constant voltage input to the system was maintained at a frequency of 75 cps, and the acoustic output of the combined system of loudspeaker and enclosure was displayed on the screen of an oscilloscope. The photographs shown in Fig. 7 were taken directly from the face of the tube. Photograph *A* is the performance of the system with the ¾-in. rear panel held in place by sixteen wood screws; this panel was lined with Kinsul insulation. Note the clean output wave form. Photograph *B* is the performance of the system with the Kinsul insulation removed from this ¾-in. back panel. Photograph *C* indicates the performance of the system with the ¼-in. plywood back held in place with sixteen screws, and photograph *D* shows the performance of the system with this ¼-in. thick back held on by only the four corner screws.

The utter deterioration of the output wave shape is due to several causes. For one, a good portion of the back radiation from the cone doesn't come out of the port at all. Much of this back wave is used up in putting this thin unsupported back into sympathetic vibration with harmonic modes of its own. This secondary radiation from the back vibrating panel, with its harmonics, blends with the primary radiation from the front of the cone, producing the deteriorated output shown. This structurally weak back panel literally becomes a parasitic radiator in the presence of the intense sound field within the enclosure. It will not be doubted that intense sound fields exist in loudspeaker enclosures. One common demonstration of the ruggedness of enclosure construction is to place a glass of water on top of the cabinet; poorly constructed cabinets will be vibrated by the internal sound pressures, causing the water in the glass to ripple. Well-constructed cabinets on the other hand will not be put into such vibration, and the water will remain perfectly placid.

This condition of high internal cabinet sound pressures may be a serious problem in large internal volumes found in the bass reflex type of loudspeaker, but the problem is even more intensified when these same high-level sound pressures are compressed into the small volumes usually found at the throat of a horn-type baffle. Any weakness of construction down at this throat that will permit panel vibration will cause even more excessive deterioration of the low-frequency response. Not only is rigidity of the individual sections of the horn important, but the sealing of the various joints is of equal importance. Leakage in these seam areas is acoustically equivalent to a high-pass filter causing a reduction of the low-frequency response of the system. It is sometimes advantageous to check for leakage in horn systems by sealing off the mouth of the horn and building up a static pressure of air within the horn. The rate at which this pressure falls off is a measure of the leakage of the system. Be it the bass reflex baffle, the horn type, or any other favorite, the acoustic performance of that baffle is a function of the mechanics involved in its construction.

Since high-fidelity has grown from the hobbyist's type of endeavor to full-fledged commercial ventures, we find that we must now deal with the interior decorator and furniture designer when it comes down to a matter of cabinets because the finished cabinet becomes truly a piece of furniture in the home. And too many interior decorators or custom builders of cabinets are prone to choose a grill cloth for appearance's sake only. They are not cognizant of the fact that the wrong choice of a grill cloth may literally destroy many dollars worth of high fidelity built into the high-frequency end of the speaker system. Figure 8 pictures some typical grill cloths and the effect of these various cloths in attenuating the high frequencies from a tweeter system. It will be observed that those grill cloths which are the thinnest and the most porous are best suited to the transmission of the high frequencies, whereas the heavy drapery type of cloth blocks these high frequencies. The thickness of the material, its fibrous nature, its degree of porosity, the method of its weaving—these are all mechanical problems that affect the acoustic output of the system.

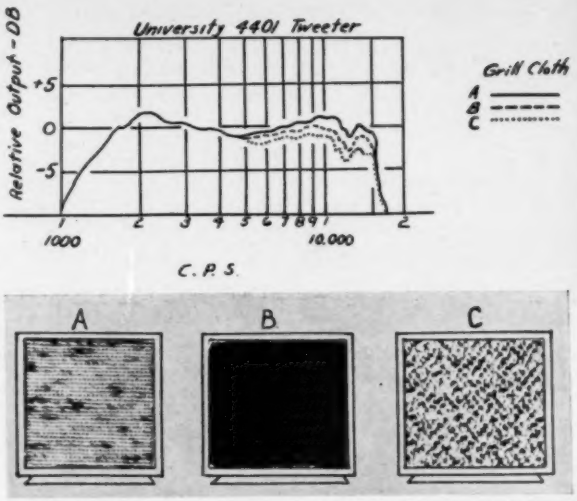

FIG. 8. The choice of the proper grill cloth will ensure minimum high-frequency attenuation of tweeter output.

And so, having started with the bare diaphragm, we have gone down the line to the end of the system, the grill cloth, integrating the system as a whole in terms of mechanical design to show that good loudspeaker design is very much a matter of good mechanical design.

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AES News

Rensselaer Chapter Elects Officers

The Rensselaer Polytechnic Institute chapter held its annual election meeting on May 11, 1954. The following officers were elected:

President:	Thomas Hill
Vice President:	Dominick Vicedomine
Secretary-Treasurer:	John McKendree
Board:	Steven Closs, John Cooley, David Lee

Section Meetings

Cincinnati

Chairman: Charles Boegli

Secretary: Joseph E. Owen, 3242 Woodburn Avenue, Cincinnati 7, Ohio

Papers: "High-Quality Loudspeakers with Emphasis on the Klipschorn," Paul W. Klipsch, Klipsch and Associates, March 26, 1954.

"A Description of the Mechanical Process Used in Assembling Multi-Voice and Multi-Speed Recording for a Radio Dramatic Program and Phonograph Recording," W. J. Mahoney, Jon Arthur & Associates, June 24, 1954.

Columbus

Chairman: J. E. Anderson

Secretary: William E. Parker, 1271 Republic Ave., Columbus, Ohio

Papers: Business Meeting, March 23, 1954.

"Rolloffs, Crossover, and Equalization," David O'Brien, Anderson High Fidelity Center, April 21, 1954.

Los Angeles

Chairman: Herbert E. Farmer

Secretary: Daniel H. Weigand, 3122 West 152 Place, Gardena, California

Papers: "Operation and Maintenance at Radio Recorders," and tour of Radio Recorders, Harry L. Bryant and Jack Lattig, Radio Recorders, March 30, 1954.

"Common Sense and High Fidelity," Roger LeFont, Universal Recorders; tour through Sound Services, Inc., led by Gordon William and Sam Donner, Sound Services, Inc., April 28, 1954.

"Berlant Broadcast Recorder," Richard Hoskin, Berlant Associates, May 25, 1954.

"Stereophonic Sound and CinemaScope," Lorin Grignon, Twentieth Century-Fox Studios, May 25, 1954.

"Operation Ivy," film; "The Stancil-Hoffman S5 Tape Recorder"; "The B-47," film; Michael Thornton, Lookout Mountain Laboratory; William Stancil, Stancil-Hoffman Corporation, June 29, 1954.

"Hi-Fi and Good Programming," Howard Rhines, Station KFAC; "The Floating Diaphragm as a Low-Frequency Radiator," William Benjamin, William Benjamin Sound Company, July 27, 1954.

New York

Papers: "Use of Audio Instruments in Tests of Hearing and Hearing Rehabilitation," Dr. M. Bergman, Hunter College, April 20, 1954.

"Factors Governing the Manufacture of Home Binaural Systems," C. E. Smiley, Livingston Electronics Corp., May 11, 1954.

"High Fidelity: History, Objectives and Trends," Hugh Knowles, Industrial Research Products, Inc., May 27, 1954.

"Transient Behavior of Electric Wave Filters," Leslie Norde, Hammarlund Mfg. Co., Inc., June 8, 1954.

San Francisco

Chairman: B. H. Smith

Secretary: Wallen W. Maybeck, 2751 Buena Vista Way, Berkeley 8, California

Papers: "A New Professional Quality Portable Tape Recorder," Jack Wernli, Ampex Electric Corp., April 12, 1954.

"The Floating Diaphragm as a Low Frequency Radiator," William C. Benjamin, Benjamin Speakers, May 10, 1954.

"Microphones; Mechano-Electrical Transducers," Robert C. Ackers, Radiation Laboratory, University of California, June 14, 1954.

"Latest Developments in Multichannel Stereophonic Theatre Sound Equipment," William E. Seaman, Ampex Electric Corp., July 12, 1954.

"New Commercial Audio Products," Hal Cox, Hal Cox' Custom Music Shop, August 9, 1954.

Rensselaer Polytechnic Institute

Chairman: Charles R. Wood

Secretary: John D. McKendree, 30 Eighth St., Troy, New York

Papers: "Problems of Preamplifier Construction," John A. Cooley, student, March 24, 1954.

"Testing the G.E., Fairchild, and Pickering Pickups," William H. Hernstadt, student, March 24, 1954.

"The New Heathkit Preamplifier and Single-Chassis Williamson Amplifier," David Glassman, student, April 20, 1954.

Public Demonstration of Binaural Sound Reproduction, April 28, 1954.

Business Meeting, May 11, 1954.

Journal Authors

R. E. CARLSON was born in Los Angeles, California, in 1911. A Phi Beta Kappa, he received his B.A. degree from Pomona College, majoring in physics and music. In 1933 he received his M.S. degree from Dartmouth College, where he was a teaching fellow in physics. He then went to New York City for private piano study. From 1934 to 1935 he taught piano and gave concerts. In 1935, he joined the faculty of Cate School, teaching mathematics, science, music and photography. During World War II, Mr. Carlson was a lecturer in physics at Pomona College in the Army Pre-Meteorology Program. Later he did development work in radar and guided missiles at the Massachusetts Institute of Technology. In 1946 he returned to Cate School as Director of Studies and taught mathematics and science. In 1949, Mr. Carlson established his own business of custom-built sound systems and home installations in Santa Barbara, California. In 1953 he joined Sherman Fairchild and Associates and Fairchild Recording Equipment Company as a consultant in research and development.

From 1930, Mr. Calson has been active in photography and choral directing and has served as organist in a number of churches in Santa Barbara.

ABRAHAM B. COHEN

ABRAHAM B. COHEN was born in Boston, Massachusetts, in 1910. During his pre-university days, he was Concert Master of the Boston School Symphony Orchestra and first violinist with the Boston Civic Symphony Orchestra. He attended Northeastern University, Boston, receiving his B.E.E. degree in 1932 and his B.S. degree in 1933. Mr. Cohen was employed by radio station WCAU in Philadelphia from 1934 to 1936, where, as studio control engineer, he was generally concerned with the production of programs originating with the Philadelphia Symphony Orchestra, the Curtis Institute of Music, and the Robin Hood Dell Concerts. In 1936 he went to Westinghouse station KYW in Philadelphia as master control engineer, and remained there until 1942. During the year 1941-1942, Mr. Cohen did graduate work in mathematics and acoustics at the University of Pennsylvania. The next year he went to Metropolitan Television in New York as chief engineer to design, build, and put into operation FM station W75NY (subsequently reclassified as WABF), and worked on experimental television station W2XMT. In 1943, Mr. Cohen joined Best Manufacturing Co. as senior acoustic engineer, and in 1945 he went to Radio Receptor Co. as engineering supervisor in the Thermatron division. In 1947 he joined University Loudspeakers, Inc., as laboratory supervisor in charge of their research laboratories. At the present time, Mr. Cohen is their manager of the engineering department.

The author of a number of papers on loudspeakers, acoustics, and music, Mr. Cohen holds two patents on loudspeakers. He is a member of the AES, the Acoustical Society of America, and the IRE.

ALFRED JORYSZ

ALFRED JORYSZ was born in Vienna, Austria, in 1913. He attended the Vienna Institute of Technology and received the degree of M.S. in applied physics and radio engineering in 1937. In 1938 he was employed by the Presto Recording Corporation as a test and development engineer in the audio amplifier and disk-recording field. From 1941 to 1945, Mr. Jorysz was a project engineer on several U. S. Navy war contracts involving development work on sonar systems, sonar test equipment, special recording devices, and aerial navigation trainers. Since 1945, he has been the engineer in charge of the electronics laboratory of the Presto Recording Corporation, supervising the design and development of all types of instantaneous recording systems. Mr. Jorysz is a member of the IRE.

OTTO KORNEI

OTTO KORNEI was born in Vienna, Austria, studied electrical engineering and physics, and received engineering degrees from the Institutes of Technology in Vienna and Berlin. In Europe he worked first in the field of fascimile transmission; later, he became associated with the largest German sound film concern, where he was in charge of a subsidiary's technical activities, concerning photographic, magnetic, and disk recording.

He came to the United States in 1938, when he cooperated, as a consulting engineer in New York City, in the development of the process now known as Xerography.

Mr. Kornei joined the Brush Development Company in 1939. Since then he has been mainly concerned with questions related to mechanical and magnetic recording of information. His work has comprised investigations of basic problems as well as the development of various transducer devices in the disk and magnetic recording field. These included, among others, the first magnetic head for the Armed Forces during World War II, crystal record cutters, and a great variety of special magnetic heads.

For several years, Mr. Kornei has been in charge of the group working on magnetic recording research and development; in the new Clevite-Brush Development Company, specifically, he is head of the Magnetic Components Development.

Mr. Kornei is the author of several well-recognized technical publications and the originator of about twenty domestic and foreign patents.